# ULF Wave Observations at the End of 2024

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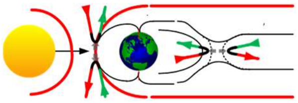

Ultralow Frequency Waves (*ULF Waves*) are periodic electromagnetic waves in Earth's magnetosphere that can be observed by ground magnetometers; they are seen as low amplitude, rapidly varying traces on a 24 hour magnetogram. ULF waves have frequencies of a few mHz to a few Hz, corresponding to periods from several minutes to fractions of a second. This article describes ULF Waves observed on 17 December 2024 with the SAM-III magnetometers at Anchorage Radio Observatory and HAARP Radio Observatory in Alaska (figure 1). A comprehensive description of ULF Waves and observations in Alaska in 2023 is given in [Reeve23].


Figure 1 ~ Map of Southcentral Alaska showing the locations of Anchorage Radio Observatory (left marker) and HAARP Radio Observatory (right). The great circle distance between the two, shown by the black line, is 286 km. HAARP is 2° farther north in magnetic latitude than Anchorage and 4° east in longitude.

Geomagnetic coordinates:
Anchorage: 61.72° N : 94.41° W (2022)
HAARP: 63.62° N : 90.42° W (2024)

Note: Geomagnetic coordinates change over time because of the wandering nature of Earth's internal dipole field.

Image source: http://www.movable-type.co.uk/scripts/latlong.html

Near-Earth Magnetic Conditions: The shock wave associated with multiple coronal mass ejections (CME) from 13 and 14 December was observed at 0445 on 17 December by the ACE spacecraft. At that time the component of the interplanetary magnetic field (IMF) aligned with Earth's dipole axis (Bz) reached a maximum of –20 nT (southward). Soon after, the total field (Bt) increased from about 8 nT to 30 nT and the solar wind speed increased from about 400 to 650 km $s^{-1}$ (https://www.swpc.noaa.gov/products/ace-real-time-solar-wind ). The disturbed magnetic conditions on 17 December expanded the auroral oval southward so that both Anchorage and HAARP observatories were directly under it (figure 2).

Local Magnetic Conditions: Magnetograms show the local magnetic field flux density vectors over a 24-hour period. The Anchorage and HAARP magnetograms show the magnetic field components in the geographic coordinate system with the Bx-component oriented true north-south, By-component oriented true east-west and Bz-component oriented vertical. ULF Waves are generally seen only in the Bx- and By-components and are quite clear in the latter two-thirds of the 17 December magnetograms (figure 3).

Close examination of the magnetograms show a Sudden Impulse from the CMEs of approximately 40 nT amplitude at 0519 followed immediately by magnetic storm conditions. Under these conditions, the impulse event more correctly is called a *Storm Sudden Commencement* (SSC).

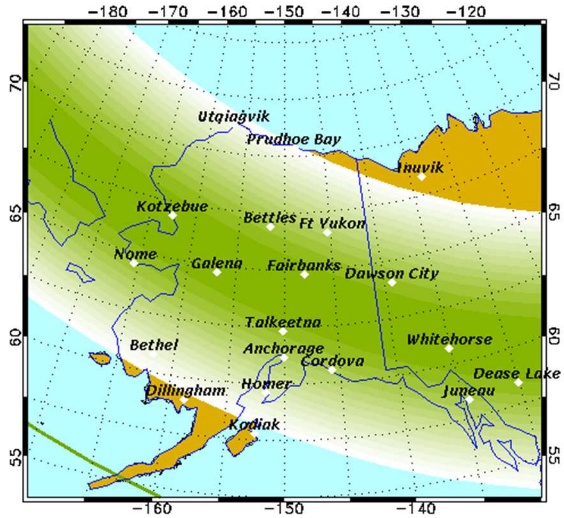


Figure 2 ~ Forecasted Auroral Oval for 17 December. Anchorage is at lower-middle of the map, HAARP is not marked. The green gradient indicates the probability of viewing the aurora.

The Auroral Oval maps the footprints of open magnetic field lines that allow energetic particles in the solar wind to enter the magnetosphere where they can enable the production of ULF Waves.

Image source: [https://www.gi.alaska.edu/monitors/aurora-forecast](https://www.gi.alaska.edu/monitors/aurora-forecast)

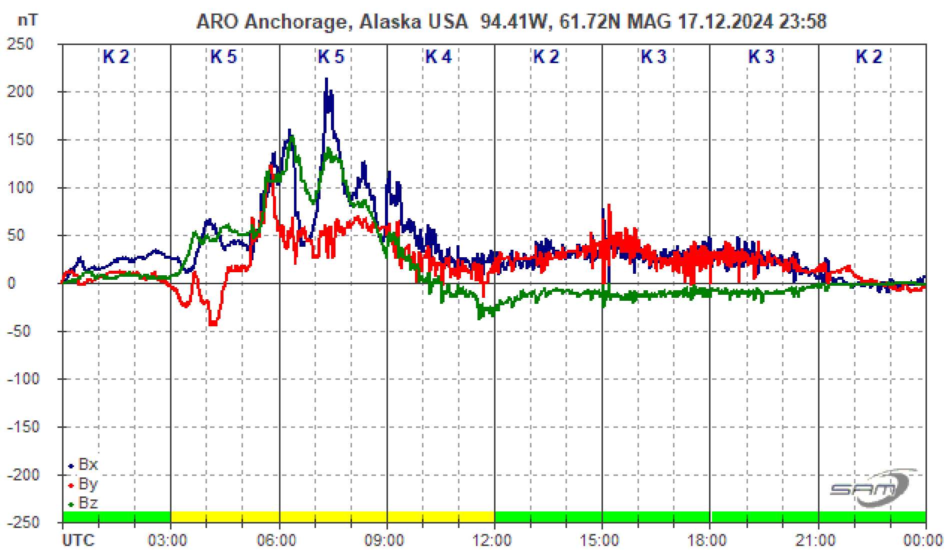


Figure 3.a ~ Magnetogram for Anchorage for 17 December. The ULF Waves, seen as low amplitude "noisy" traces appear to start about the same time as the disturbance (K5) at about 0720 UTC and continue to at least 2100. Local solar midnight is 1000 UTC, so these times correspond to local solar times in the pre-midnight-to-dawn sector. Note that the ULF Waves are indicated only in the Bx (blue trace) and By (red trace) components of the magnetic field.

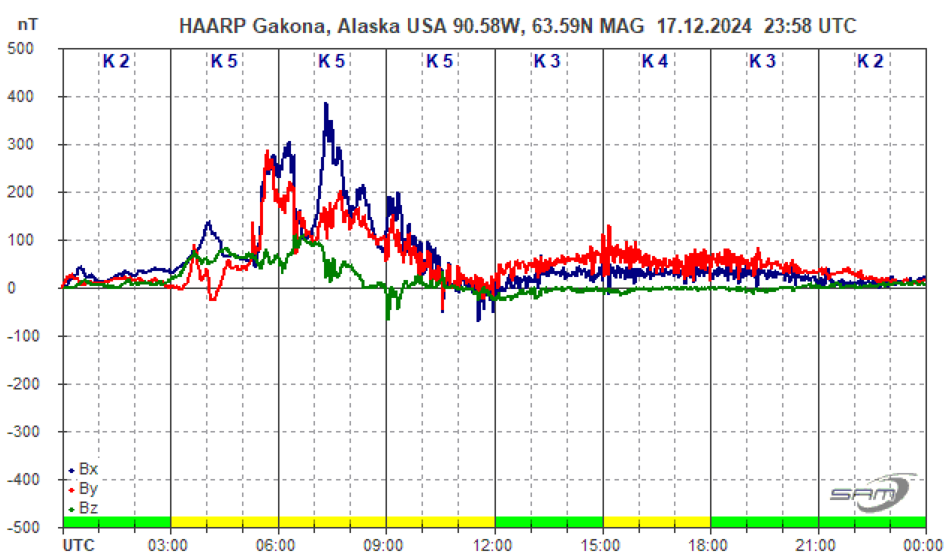


Figure 3.b ~ Magnetogram for HAARP for 17 December. Only minor differences are seen throughout the day compared to Anchorage. Some differences are due to the position of the auroral electrojets and some could be distortion of the magnetic field by local geology. Although the K-Index values for each 3-hour synoptic period also show some differences throughout the day they do track very closely over longer time periods.

ULF Waves: The brief descriptions in this section are adapted from {Reeve23}. ULF Waves are divided into two basic types, *continuous* and *irregular*, based on how they appear in ground magnetometer records such as a magnetogram. The continuous pulsations are quasi-sinusoidal lasting more than several cycles (sometimes several hours) whereas the irregular pulsations are relatively short-lived (less than a few cycles). The generally accepted frequency ranges and corresponding periods are listed in table 1.

Table 1 ~ ULF Wave Classifications

| Type | Name | Frequency (mHz) | Period (s) |
|---|---|---|---|
| Continuous Pulsations | Pc 1 | 200 – 5000 | 0.2 – 5 |
| | Pc 2 | 100 – 200 | 5 – 10 |
| | Pc 3 | 22.2 – 100 | 10 – 45 |
| | Pc 4 | 6.7 – 22.2 | 45 – 150 |
| | Pc 5 | 1.7 – 6.7 | 150 – 600 |
| Irregular Pulsations | Pi 1 | 25 – 1000 | 1 – 40 |
| | Pi 2 | 6.7 – 25 | 40 – 150 |

Pc 5 waves with specific frequencies consistently appear in detailed spectral analyses and are called *magic frequencies*: 0.7, 1.3, 1.9, 2.6 – 2.7, 3.2 – 3.4, and 4.8 mHz (see {Reeve23}). The frequencies are observed to vary a little depending on the study. Statistical studies show these frequencies, or frequencies close to them, occur in the solar wind upstream of the magnetosphere as well as in the dayside magnetosphere. The wavelengths of Pc 3, Pc 4 and Pc 5 waves are comparable to the size of the magnetosphere.

Data Analysis: The plots in this section are based on the local magnetic field horizontal component H, which is the vector sum of Bx and By. H is calculated during post processing of the data from each observatory. Time domain plots of H for the full 3-hour period from 1500 to 1800 are followed by plots of the Fast Fourier Transforms (FFT) of that data (figure 4). The FFT converts the serial time domain data to the frequency domain and allows identification of specific frequencies in the ULF Wave spectra. The spectra plots for the full 3-hour time period extend to 50 mHz with annotations of the higher amplitude components.

Subsequent time domain and frequency domain plots (figures 5, 6 and 7) show shorter overlapping time periods 1500 to 1630, 1600 to 1730 and 1700 to 1800. The time periods were arbitrarily chosen and have no other significance. The frequency range shown for these shorter time periods is reduced to 10 mHz because, as seen in the plots for the full 3 hour period, spectra above 10 mHz are very weak by comparison.

All FFTs were calculated using the Hamming window to reduce spectral leakage. The FFT calculations were performed in Microsoft Excel 2019 using raw magnetometer data that has been normalized to the start of each time period. No effort was made correct or compensate for any amplitude errors resulting from the windowing or transform. The time domain plots show the actual, uncorrected recorded magnetic flux density and have not been normalized.

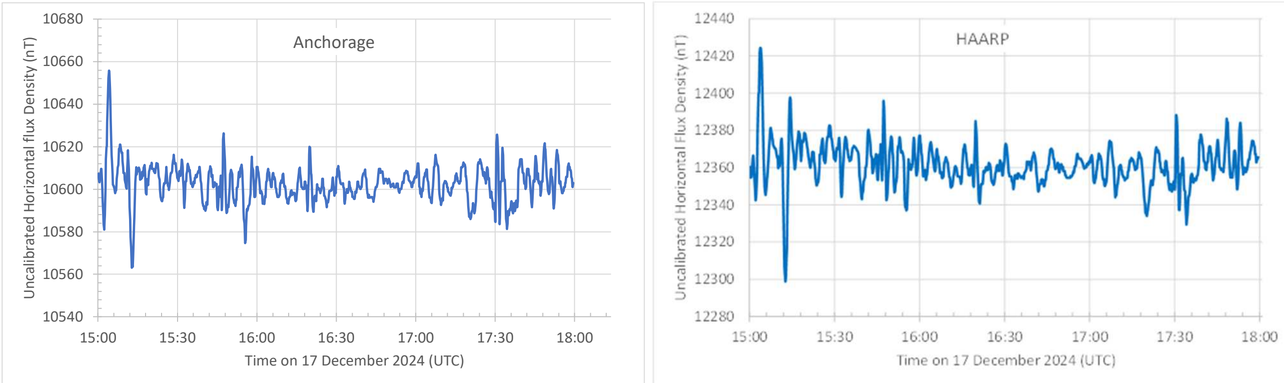


Figure 4.a ~ Time domain plots for Anchorage (left) and HAARP (right): Abridged magnetogram showing the time period from 1500 to 1800 UTC. Several periodicities are visible and possibly an irregular (single cycle) pulsation near the beginning. The vertical scales are uncalibrated. For comparison, the calculated H-component intensity using the World Magnetic Model WWM-2020 for 17 December was 15 156 and 13 977 nT for Anchorage and HAARP, respectively.

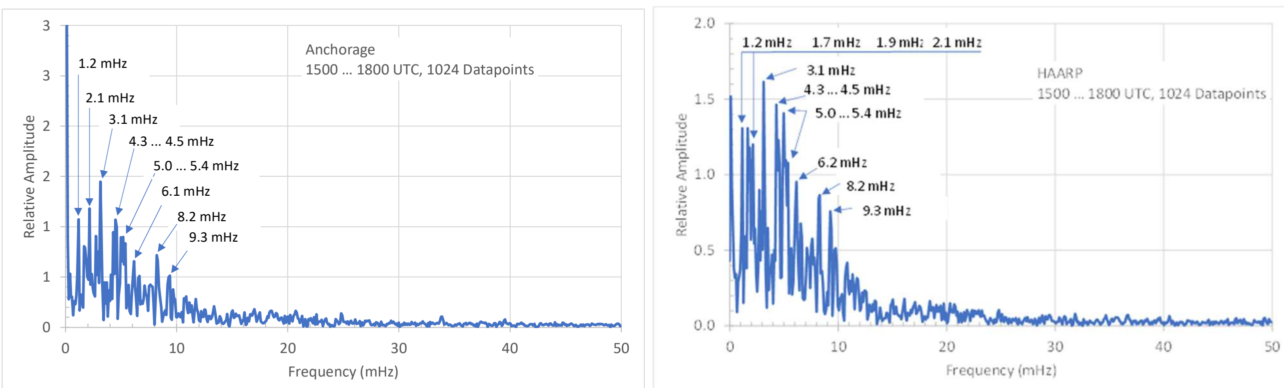


Figure 4.b ~ Frequency domain plots of data from figure 4.a calculated using the FFT; frequency resolution is 0.1 mHz. The full 50 mHz frequency range is shown although any spectra above about 10 mHz is very weak. Pc 4 (6.7 to 22.2 mHz) and Pc 5 (1.7 to 6.7 mHz) pulsations are labeled. The 4.3 to 4.5 and 5.0 to 5.4 mHz frequencies overlap, possibly indicating drift during the 3 hour period.

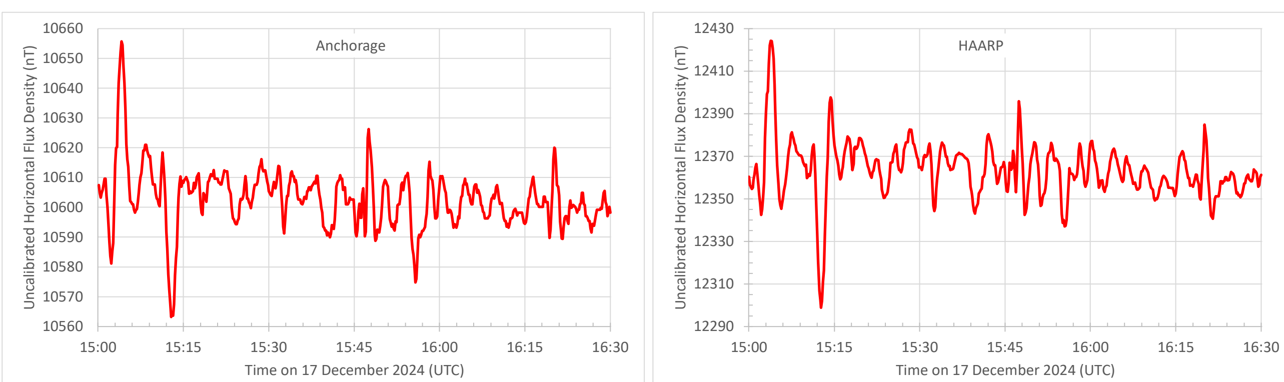


Figure 5.a ~ Time domain plots for Anchorage (left) and HAARP (right): Abridged magnetogram showing the 1.5 hour time period from 1500 to 1630 UTC. The irregular pulsation near the beginning is more apparent than in the plots for the full 3-hour period. The vertical scales are uncalibrated.

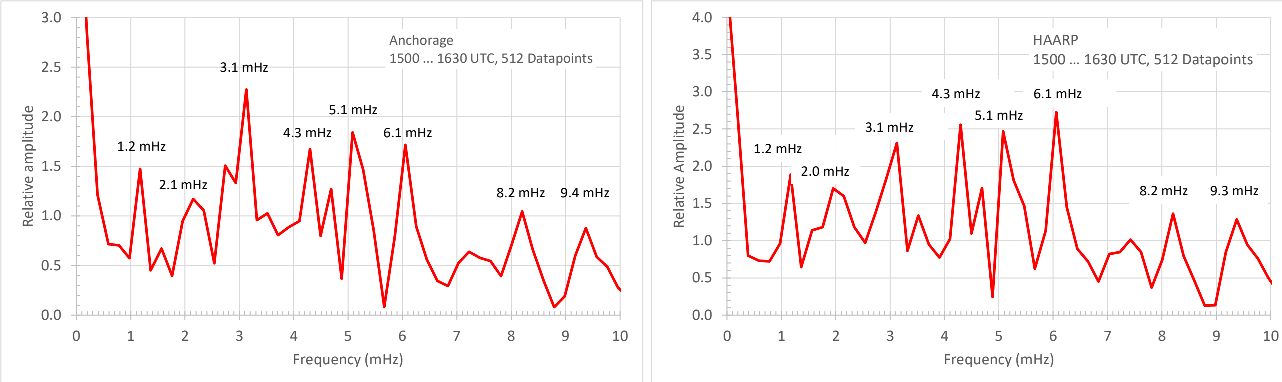


Figure 5.b ~ Frequency domain plots of data from figure 5.a. The plotted frequency range has been reduced to 10 mHz; frequency resolution is 0.2 mHz. Pc 4 (6.7 to 22.2 mHz) and Pc 5 (1.7 to 6.7 mHz) pulsations are visible and the two observatories show remarkable correlation.

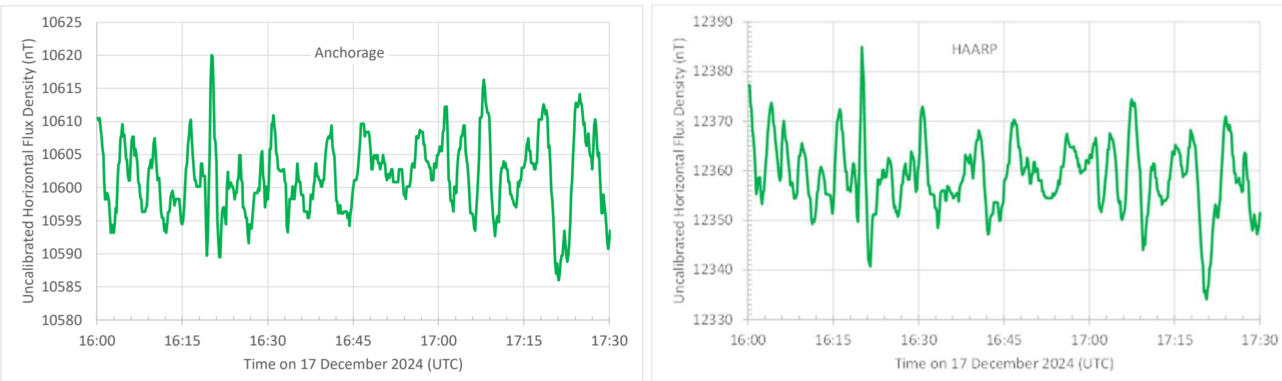


Figure 6.a ~ Time domain plots for Anchorage (left) and HAARP (right): Abridged magnetogram showing the 1.5 hour time period from 1600 to 1730 UTC. A possible Pi is visible at about 1620.

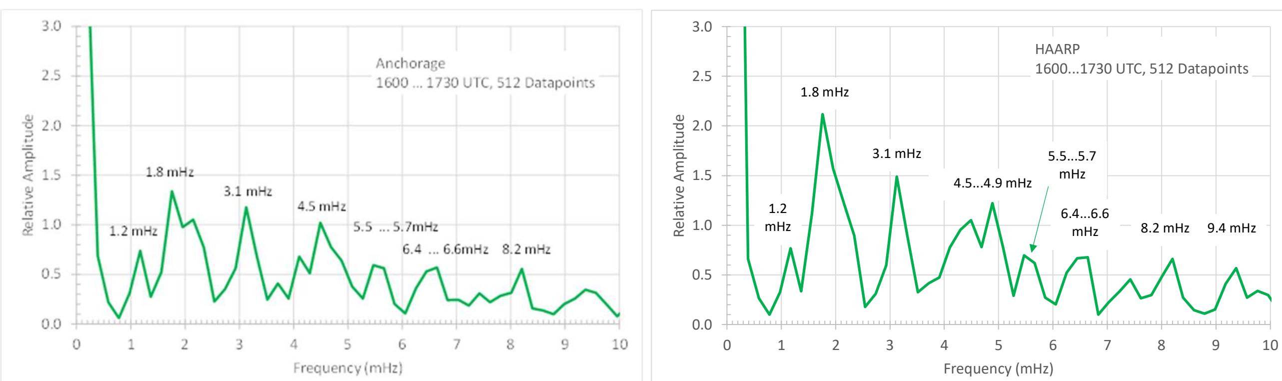


Figure 6.b ~ Frequency domain plots of data from figure 6.a. As above, the frequency range has been reduced to 10 mHz and frequency resolution is 0.2 mHz.

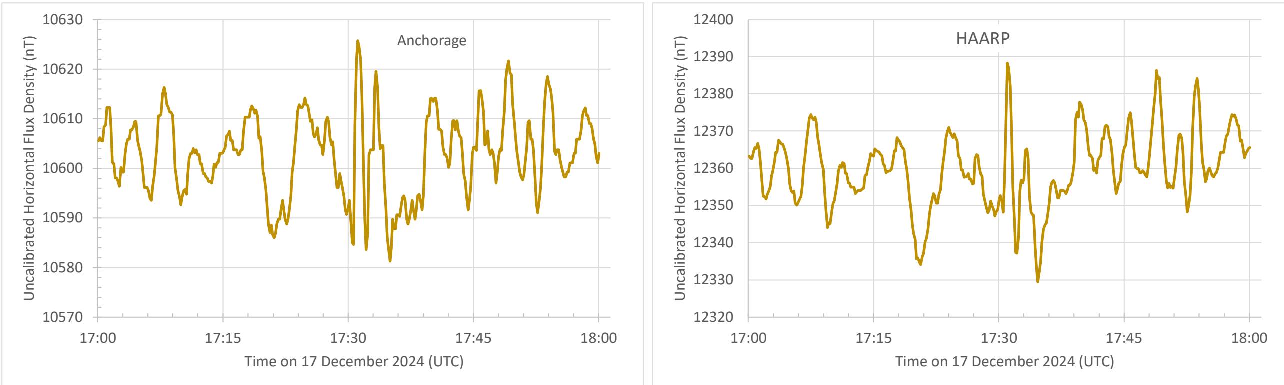


Figure 7.a ~ Time domain plots for Anchorage (left) and HAARP (right): Abridged magnetogram showing the 1 hour time period from 1700 to 1800 UTC. A possible Pi is visible about 1735. The resemblance between the two observatories is very high.

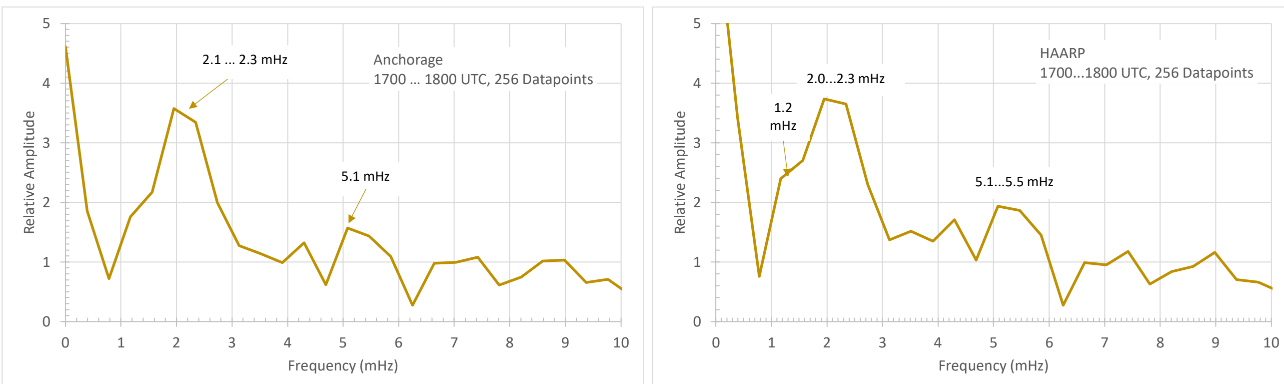


Figure 7.b ~ Frequency domain plots of data from figure 7.a for the time period from 1700 to 1800 UTC; frequency resolution is 0.39 mHz. During this time period, the peaks are not sharp due to the lower frequency resolution, and there are not nearly as many peaks visible compared to earlier time periods. As with the time domain plot, the resemblance is very high between the two observatories.

Discussion: The time domain (magnetograms) and frequency domain (FFT) plots are remarkably the same for the two observatories, not only for the entire 3-hour time period but also the individual 1.5- and 1-hour segments. This is not particularly surprising given the close proximity of the two observatories (286 km), but it serves to increase confidence in the observations and calculations.

ULF Waves are often observed in the Anchorage and HAARP magnetograms throughout the year, but they do not always persist for the long period observed on 17 December. In terms of a solar time scale, the ULF Waves seen in the magnetograms occurred in the midnight through dawn to the noon time sectors (figure 8). These ULF Waves started coincidentally with the magnetic disturbance caused by multiple CMEs and likely are related to them.

The inverted magnetic bays seen in the above Anchorage and HAARP full-day magnetograms between 0700 and 1000 occurred soon after the CMEs arrived. The impact caused the auroral oval to expand and the auroral electrojets to flow directly overhead of both Anchorage and HAARP. The inverted bays indicate an enhancement of the local magnetic fields, although the enhancements amounted to only 1% of the ambient Bx-component (north-south) at Anchorage and 3% at HAARP.

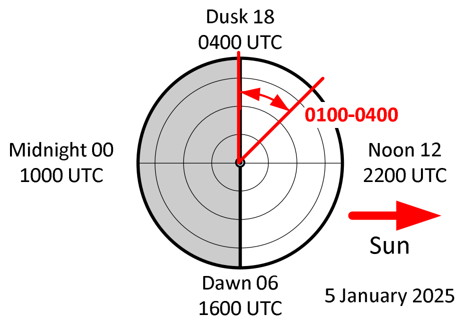


Figure 8 ~ Solar time scale for Anchorage with corresponding times in UTC. UTC times at HAARP are 20 minutes earlier. The ULF Waves on 17 December occurred in the midnight-to-dawn and dawn-to-midnight sectors. The waves discussed in this article were detected around local solar dawn and may have been caused by shear between the relatively higher speed CME plasma and Earth's magnetosheath.

The so-called *magic frequencies* (see {Reeve23}) are clearly visible in the FFT plots for both observatories and they are almost identical (table 2). Other frequencies are visible at both observatories. Most, but not all, frequencies fall into the Pc 5 range (1.7...6.7 mHz). The observations of higher frequencies in the Pc 4 range (6.7...22.2 mHz) may be limited by the sample rate setting of the two SAM-III magnetometers (10 seconds). Some spectral peaks seen in the FFT plots are relatively broad and may indicate frequency drift, spectral leakage or simply the result of relatively low frequency resolution.

Table 2 ~ Frequencies observed for Continuous Pulsations (Pc) taken from FFT plots for all time periods

| **Observatory** | **Frequencies, Pc 5: 1.7 ~ 6.7 mHz** | **Frequencies, Pc 4: 6.7 ~ 22.2 mHz** |
|---|---|---|
| Anchorage | 1.2, 1.8, 2.1...2.3, 3.1, 4.3...4.5, 5.0...5.4, 5.7, 6.1, 6.4...6.6 | 8.2, 9.3...9.4 |
| HAARP | 1.2, 1.7, 1.9, 2.0...2.3, 3.1, 4.3...4.5, 4.5...4.9, 5.0...5.4, 5.5...5.7, 6.1...6.2, 6.4...6.6 | 8.2, 9.3...9.4 |

Instrumentation: The SAM-III Magnetometer installations at Anchorage and HAARP are nearly identical (figure 9). The differences are listed in table 3. Both stations use the SAM_VIEW software to display and log the three magnetic components. Real-time magnetograms are available at: https://reeve.com/SAM/SAM_simple.html (Anchorage) and https://reeve.com/SAM/SAM-HAARP/SAM-HAARP_simple.html (HAARP).

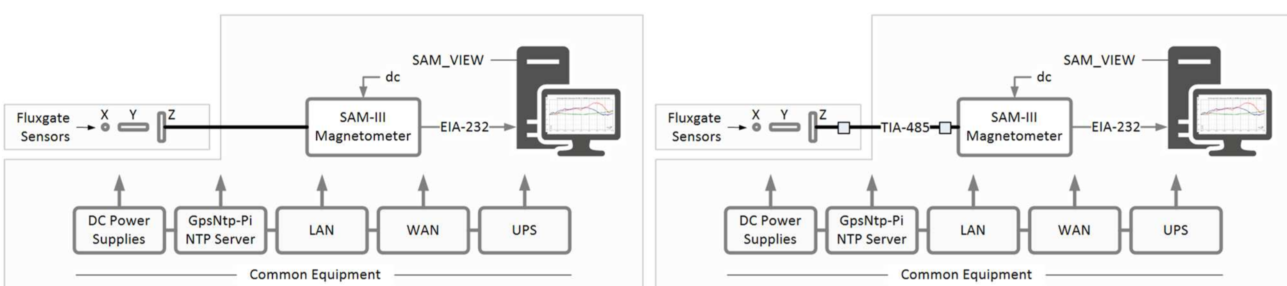


Figure 9 ~ SAM-III Magnetometer block diagrams for Anchorage (left) and HAARP (right). The two are operationally identical and differ only in a few technical details (see table).

Table 3 ~ Differences between magnetometer stations

| Observatory | Anchorage | HAARP | Remarks |
|---|---|---|---|
| Sensor type | FGM-3 | FG-3+ | Performance nearly identical |
| Sensor voltage | 12 Vdc | 5 Vdc | Anchorage has 5 V voltage regulators at the sensors whereas HAARP has them on the controller |
| Sensor transmission | Cable only | TIA-485 + Cable | HAARP uses CAT5E cable and TIA-485 transmission interfaces |

References:

{Reeve23} Reeve, W., Observations of ULF Waves at Anchorage, Alaska, 2023: https://reeve.com/Documents/Articles%20Papers/Reeve_ULFWaveObsrv.pdf

Readers may refer to articles about ULF Waves and other geomagnetic phenomena observed and recorded by the SAM-III magnetometers in Alaska: https://reeve.com/RadioScience/Radio%20Astronomy%20Publications/Articles_Papers.htm#Observations

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0.2 (Added HAARP magnetograms & FFT plots, 23 Dec 2024)
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