Spring 2013

A statistical analysis of Electromagnetic Ion Cyclotron (EMIC) waves and their correlation to the 11-year solar cycle

Erik A. Lindgren
University of New Hampshire - Main Campus, erikanderslindgren@hotmail.com

A statistical analysis of Electromagnetic Ion Cyclotron (EMIC) waves and their correlation to the 11-year solar cycle

Erik Lindgren
The University of New Hampshire
Senior thesis – spring 2013

Abstract

This thesis presents a statistical analysis of EMIC waves measured at Halley Research Station from 2008 through 2012. An introduction covering the origin of and theory behind EMIC waves is provided, along with a background covering previous statistical research regarding EMIC waves. Guidelines regarding EMIC wave definition and analysis are described along with examples of how they were used. The data shows an increase in the total number of EMIC waves as well as the number and percentage of EMIC waves with maximum frequency above 1 Hz during the 5-year period. The results suggest that the total number of EMIC waves and the proportion of EMIC waves with maximum frequency above 1 Hz increase with increasing solar activity. A future perspective in EMIC wave research is also provided.

Table of Contents

Introduction

In the plasmapause region, there is a spatial overlap between the ring current plasma and the plasmaspheric plasma [1]. The ring current plasma is energetic and has a temperature anisotropy measured with respect to the dc magnetic field while the plasmaspheric plasma is comparatively dense and cold, and this enables amplification of ion cyclotron waves. In these conditions, Electromagnetic Ion Cyclotron (EMIC) waves can be generated in the equatorial region of the plasmasphere-magnetosphere [2]. The generation occurs during wave-particle interaction with ring current ions, and for EMIC waves in the 0.1-5 Hz frequency range (Ultra Low Frequency range, or ULF range) that can be observed on ground-level, the wave-particle interactions mostly involve protons but also heavy ions [1]. EMIC wave formation occurs mainly when the temperature anisotropy in ring current ions causes a cyclotron instability, which in turn generates the EMIC waves. Energetic protons (10-100 keV) are thought to provide most of the free energy needed to cause and maintain the wave-particle instability [2].

After being generated, EMIC waves can propagate to ground level by traveling along magnetic field lines. Measurements of waves in the ULF range have been conducted at Halley Research Station in Antarctica since February 17th 2005 [3]. The research station uses Search-Coil Magnetometers assembled at the University of New Hampshire for ULF measurements. The magnetometers have 160,000 turn coils of number 36 copper wire mounted on annealed mu-metal cores [4]. The

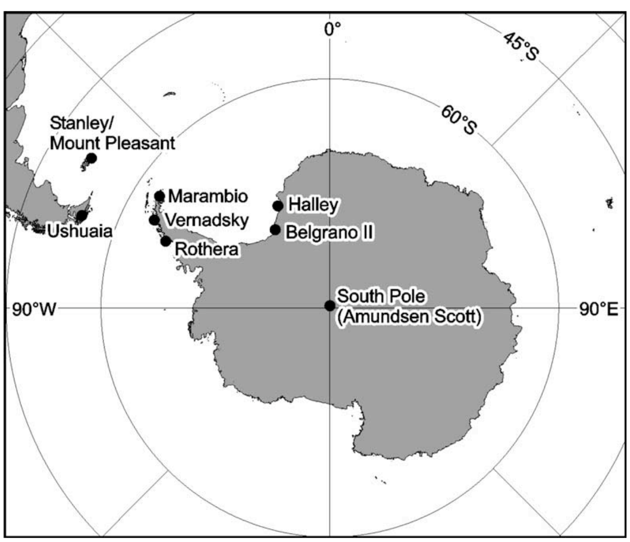

Figure 1 Picture of Antarctica showing Halley Research Station, from [5].

cores are 0.8 meter long and 2.5 cm in diameter. The instruments' resolution is approximately 10 pT at a given frequency. Figure 1 shows the location of Halley Research Station.

This thesis uses data from Halley Research Station to support a statistical analysis of EMIC waves from 2008 through 2012. Specific guidelines regarding EMIC wave definition and analysis were created in order to keep consistency throughout the 5-year period. The analysis included counts of total number of EMIC waves and EMIC waves with maximum frequency above 1 Hz (from here on referred to as *above 1 Hz*), start and end time of each wave, and maximum and minimum frequency of each wave. This data was used to find the percentage of EMIC waves above 1 Hz, average EMIC wave duration and average EMIC wave frequency range. The results were presented as monthly averages and totals, yearly averages and totals, and 2008 through 2012 monthly averages and totals. The amount of missing data was also recorded and presented.

The results were compared to the 11-year solar cycle, and a connection between EMIC waves and the solar cycle was established. A seasonal dependence of EMIC waves was also noticed. A future perspective of EMIC wave research is provided at the end of the thesis.

Background

A lot of research related to EMIC waves has been conducted, but most similar to this thesis was a statistical analysis of Pc1 waves (waves in the 0.2-5 Hz range), published by Guglielmi et al. in 2006 [6]. The time interval of their analysis ranged from 1957 to 1992, and was at the time the largest in literature. The analysis covered almost four solar cycles, from the 19th to the 22nd. They found that Pc1 occurrence was inversely dependent on solar activity, with a correlation coefficient r = -0.82. Figure 2, from Guglielmi et al., shows the inverse correlation between Pc1 waves and solar cycles.

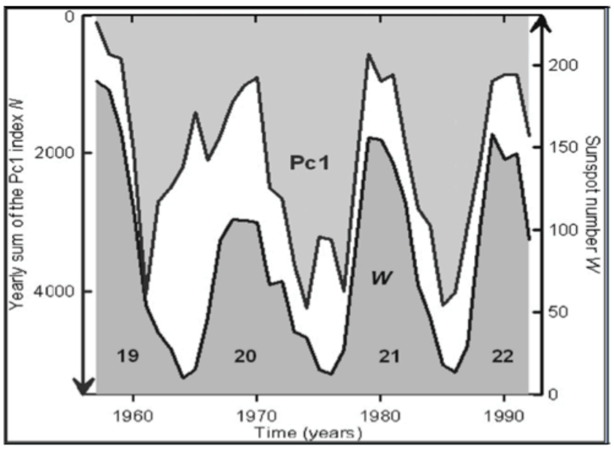

Figure 2 The inverse correlation between Pc1 waves and solar cycles, from Guglielmi et al.

The work presented in this thesis started after professor Marc Lessard of the University of New Hampshire noticed an increase in the number of EMIC waves above 1 Hz during 2012. I began the statistical analysis in March 2012, and the analysis was finished in early April 2013. Preliminary results were presented at the 2013 Undergraduate Research Conference at the University of New Hampshire on April 24th 2013.

Data Acquisition

The data from Halley was accessed via the British Antarctic Survey's website [3]. Every plot shows 24 hours worth of data on three axes (BX, BY, BZ), and the data can be viewed on a 5 or 1 Hz vertical axis. The two plot types will from here on be referred to as the *5 Hz plot* and *1 Hz plot*, respectively. Figure 3 shows data displayed on a 5 Hz plot while figure 4 shows data on a 1 Hz plot.

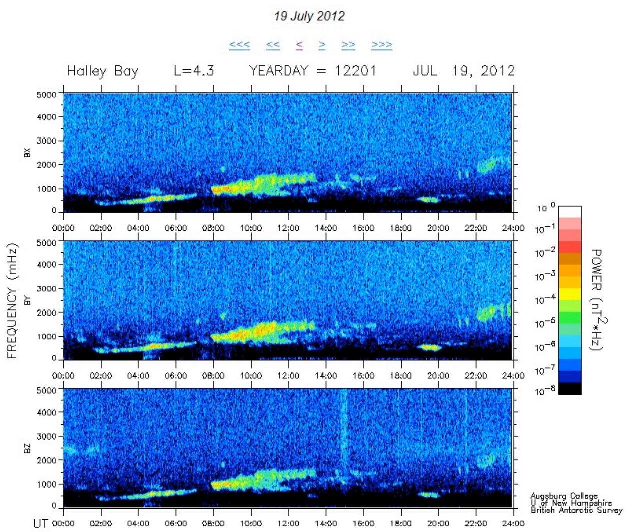

Figure 3 Example of data on a 5 Hz plot.

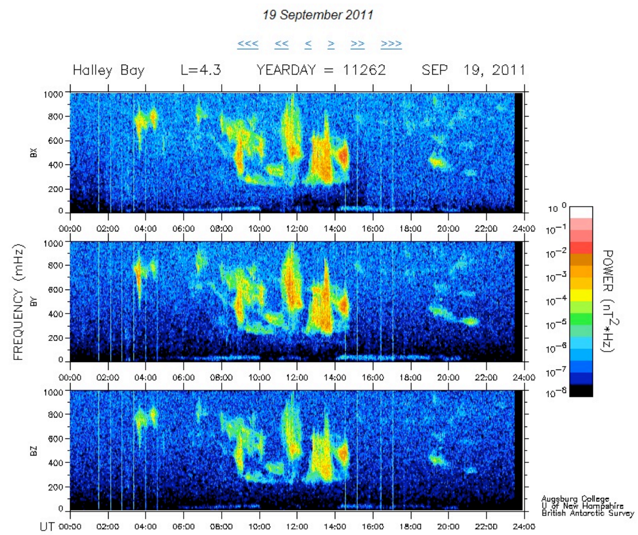

Figure 4 Example of data on a 1 Hz plot.

The EMIC wave occurrences were counted and analyzed manually. The analysis of each wave included start and end time, minimum and maximum frequency (from here on referred to and *min* and *max frequency*, respectively), duration and frequency range (max frequency – min frequency). One of the greatest challenges during the data acquisition phase of the research was defining what counts as one EMIC event. The Wave Definition and Analysis subsection describes the guidelines used in this statistical analysis.

Wave Definition and Analysis

EMIC waves are seldom easy to analyze: they can be masked by unwanted noise (i.e. registered increases in frequency that are not EMIC waves), they can be superimposed on to other EMIC waves and they can be poorly defined in terms of duration and frequency range. In order to keep consistency in the analysis of EMIC waves, these guidelines regarding the definition of the waves were put into place:

Wave Definition Guidelines (WDG)

1. An EMIC wave it is distinguishable from noise. In other words:
    a. The EMIC wave has clearly seen start and end times, and clearly seen minimum and maximum frequencies.
    b. The start *and* end times of the EMIC wave are *not* parts of the wave that reach down to 0 mHz.
2. An EMIC wave has a maximum frequency at or above 200 mHz. This is referred to as the wave *cut off frequency*. The 200 mHz cut off frequency is the same minimum frequency used by Guglielmi et al.
3. If a segment of EMIC waves (i.e. a period of time containing EMIC waves that overlap to some extent) can reasonably be assumed to be superimposed waves, the segment will be counted as individual EMIC waves to the best of my ability. Conditions that allows a segment of EMIC waves to be considered individual waves are:
    a. The segment is connected, but if it would be counted as one EMIC wave the resulting wave would be unphysical.
    b. The segment has well defined parts of different power.

c. The segment reaches maximum power on different axes.

d. The segment looks like one wave on one or two axes, but on the other axis or axes the segment is clearly separated.

4. An EMIC wave needs to be above a certain power to be counted. The so-called *cut off power* corresponds to a power on the order of $10^{-5}\ \mathrm{nT^2Hz}$, and is seen as a light green color on the plots. For an EMIC wave to be considered above cut off power, the wave needs to:

   a. Have an easily visible amount of light green color in it, on at least two axes.

   b. The only green segment of the wave is not located where the wave power is amplified by noise.

Furthermore, guidelines regarding the precision of time and frequency measurements had to be put into place. It was sometimes difficult to see where an EMIC wave started or ended, or reached max or min frequency. Even when the EMIC waves had clear start and end times, and max and min frequencies, the lack of gridlines in the plots made precise analysis difficult. The following guidelines were used in the analysis of the waves:

<u>Wave Analysis Guidelines (WAG)</u>

1. The start and end time of an EMIC wave will be determined to the closest quarter of an hour, and wave duration will therefore be measured in increments of 15 minutes. If a wave has a duration below 15 minutes, the wave will be assigned its proper start time and an end time 15 minutes after the start time, thereby assigning the wave a duration of 15 minutes.

2. If the EMIC wave is cut off by missing data, the start or end time of the wave (depending on where the wave is cut off) will be assigned as the end or start time of the data blackout. See the following subsection for more information about missing data.
3. If the max or min frequency of an EMIC wave is measured on the 1 Hz plot, the frequency will be determined in increments of 25 mHz. If the max or min frequency of an EMIC wave is measured on the 5 Hz plot, the frequency will be determined in increments of 100 mHz. Therefore, if an EMIC has a min frequency below 1 Hz but a max frequency above 1 Hz, the min frequency will be measured in increments of 25 mHz while the max frequency will be measured in increments of 100 mHz. In the event that an EMIC wave has a max or min frequency that is not visible in the 1 Hz plot but seems to be just above 1000 mHz (and below 1100 mHz) in the 5 Hz plot, the frequency will be measured as 1050 mHz.
4. If there is a discrepancy in the start or end frequencies of a wave between the 1 Hz and 5 Hz plot (from here on referred to as *1/5 discrepancy*), the 1 Hz plot will be used to determine the frequencies. If only the minimum frequency is visible in the 1 Hz plot, the frequency range will be estimated from the 5 Hz plot and the max frequency of the wave will be counted as

   max frequency = min frequency from 1 Hz plot + frequency range from 5 Hz plot **(1)**

   See the following subsection for more information about 1/5 discrepancy.

Many of these guidelines are somewhat subjective, so examples of waves where some of these guidelines were implemented are shown in figures 5 through 11.

Figure 5 shows a number of waves that are mostly split into two segments, and the way those waves were counted. The figure shows waves that are above and below 1 Hz as well as waves above and below cut off power. The segments are split up into individual waves using WDG 3a and 3b: the first segment with high power is split up mostly by its well defined parts of different power (3b), while the second segment is split up mostly because the segment would be unphysical if it was counted as one wave (3a).

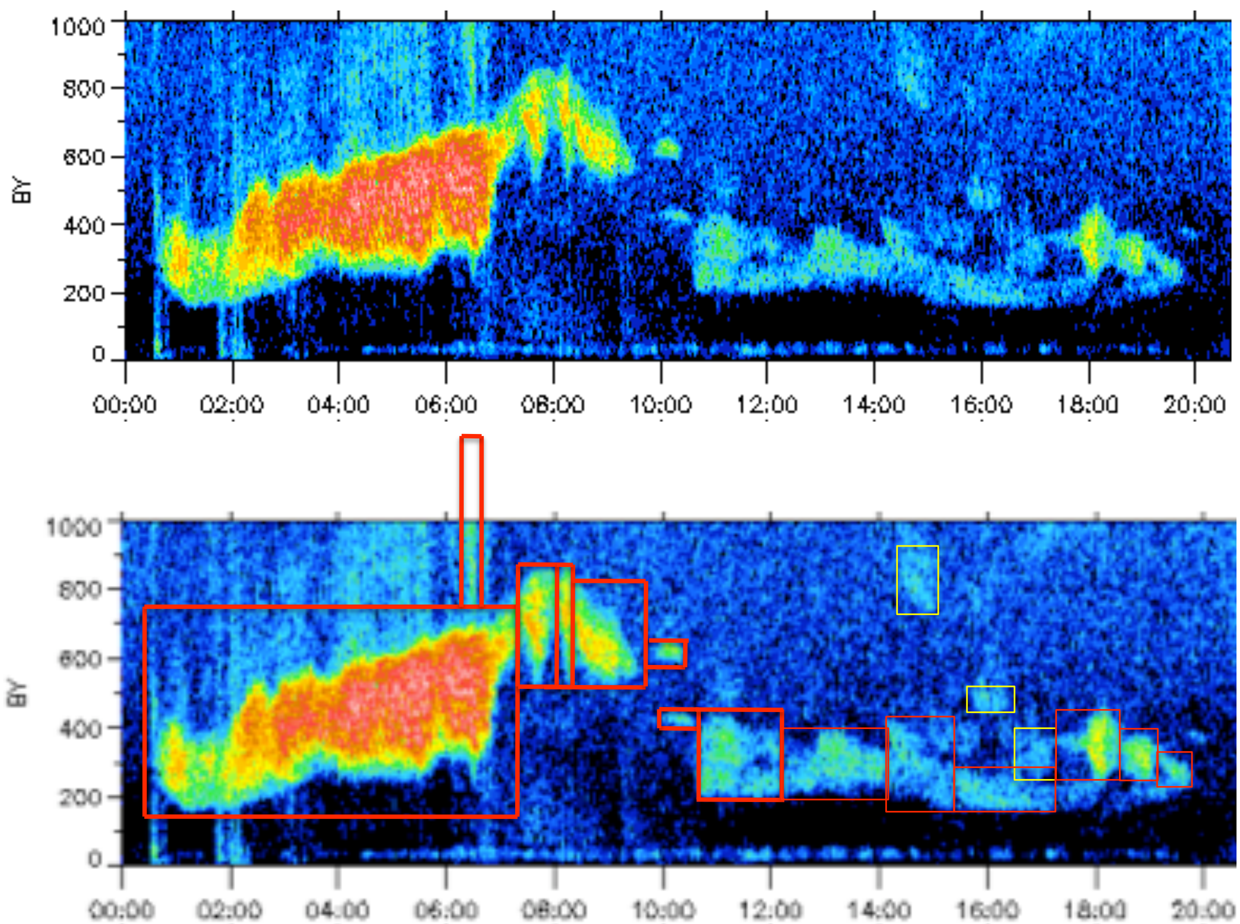

Figure 5 The upper section of the figure shows a number of EMIC waves, and the lower section shows how each individual wave was counted. One of the waves was above 1 Hz. A red box denotes a wave that was counted, a yellow box denotes a wave below cut off power.

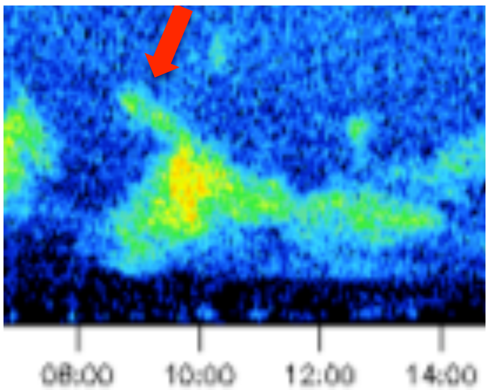

Figure 6 Example of EMIC waves that would be unphysical if they would be counted as one wave. The red arrow shows a separate wave.

Figure 6 shows another example of the application of WDG 3a. The red arrow points out a part of the segment that was counted as a separate EMIC wave. If that part of the segment wasn't considered a separate wave and the whole segment was counted as one EMIC wave, the resulting wave would start at two different frequencies and connect at a later time. That cannot be true: the segment must be split up in order to remain physical.

Figure 7 shows 24 hours worth of data containing one EMIC wave, and an enhanced view of that wave. In the enhanced view, the wave is seen to be below cut off power (WDG 4), and it was therefore not counted.

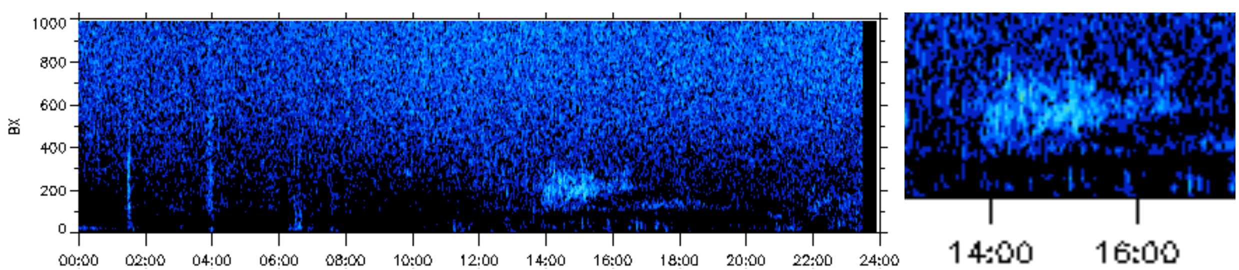

Figure 7 A day containing an EMIC wave below cut off power. The view of the wave is enhanced on the right side of the figure.

Figure 8 shows a 24-hour segment of data with three small EMIC waves below cut off frequency (WDG 2), and the enhanced view of those waves. The waves were not counted.

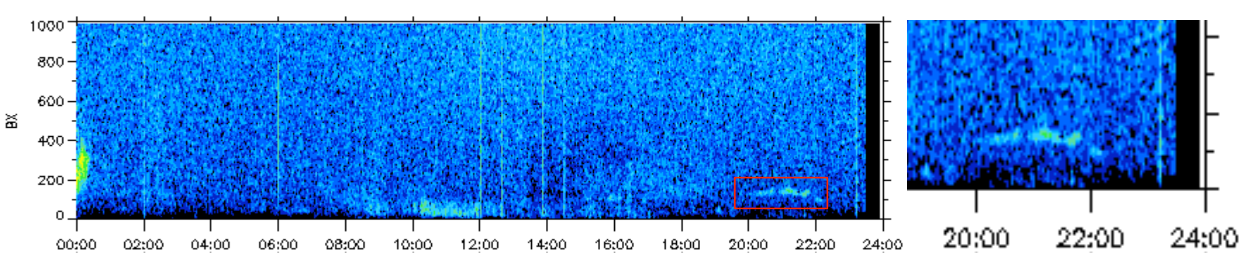

Figure 8 The red box shows EMIC waves below cut off frequency. The view of the same waves is enhanced on the right side of the figure.

An example of an EMIC wave below cut off power amplified by noise is shown in figure

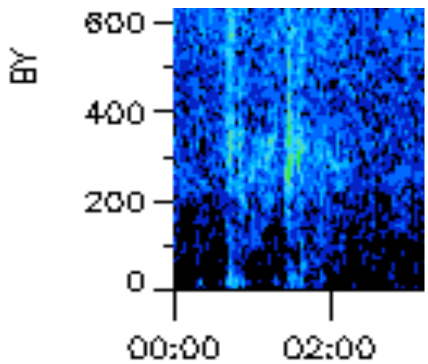

Figure 9 An EMIC wave below cut off power that is amplified by noise.

9. The only part of the wave that is above cut off power is the part that intersects with the noise (the vertical lines). Therefore, the wave does not comply with WDG 4b, and it was not counted.

Figure 10 shows a day's worth of data with some waves and a lot of powerful noise. The noise can be distinguished from the waves using WDG 1b.

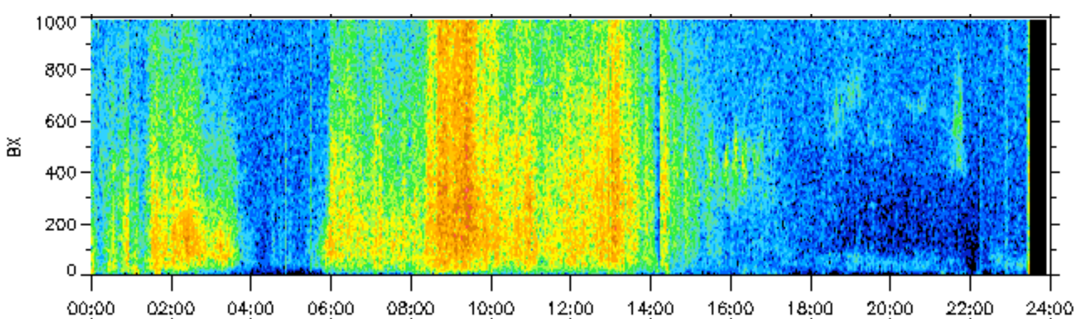

Figure 10 Example of a day with powerful noise, followed by EMIC waves.

Figure 11 shows the same segment of EMIC waves, along with two small EMIC waves, on three different axes. Two of the axes seem to show two waves in the segment (by applying WDG 3b), but another wave (with start and end time at roughly 9:30 and 10:30) can be seen in the middle plot (axis BY). That third wave was defined using WDG 3c: the less powerful, larger wave was of roughly equal power on all three axes, while the 9:30-10:30 wave reached a clear maximum power on the BY-axis.

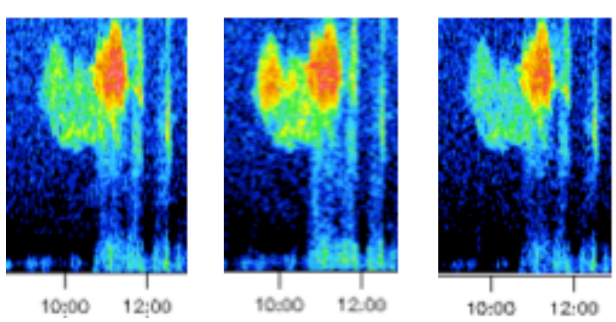

Figure 11 The same EMIC waves shown on three different axes (BX, BY, BZ from left). Notice how the middle plot shows a wave that the other two do not.

Difficulties in the Data Acquisition Process

Even with the guidelines mentioned in the previous subsection, data acquisition was difficult. A significant problem was missing data. There were “data blackouts” that lasted for several days, and these blackouts sometimes occurred during periods of intense EMIC wave activity. Figure 12 shows a day with missing data, and these data blackouts were recorded. However, noise so powerful that it could cover any EMIC waves that were there was not recorded. Figure 10 from the previous subsection shows a day with such powerful noise. Since I did not record periods of intense noise it is impossible to estimate how many EMIC waves were lost as a result of noise, but the intense noise was not a very common occurrence and appeared at most a few days per month.

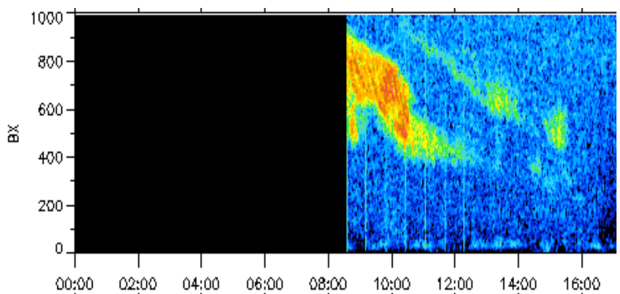

Figure 12 An EMIC wave (or two) cut off by missing data.

Another type of noise that started to occur in 2012 was a high-frequency BZ-axis noise. The noise was only visible on the 5 Hz BZ-axis, and it could last for up to a week. Given the fact it was only visible on the BZ-axis (without exception) and its extreme duration, it was considered noise and not some kind of high frequency EMIC wave. Figure 13 shows a day’s worth of data on the 5 Hz plot, containing powerful BZ-axis noise. The noise was sometimes difficult to distinguish from actual EMIC waves, but it did not impede detection of

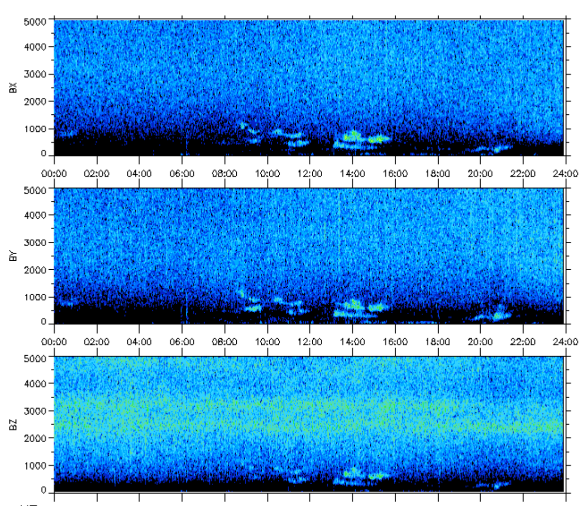

Figure 13 Example of BZ-axis noise.

EMIC waves since any wave that was covered by the BZ-axis noise would still be seen on the other axes.

Every 1 Hz plot was missing data from 23:30 until 24:00, but that was a minor problem since the 5 Hz plot showed that data. If an event was located during that 30 minute window, its max and min frequencies were determined from the 5 Hz plot. The missing 30 minutes of data in a 1 Hz plot can be seen in figures 7, 8 and 10.

A major problem in the data acquisition was the 1/5 discrepancy. EMIC waves, which had well defined start and end frequencies in the 1 Hz plot, would sometimes be shifted towards higher frequencies in the 5 Hz plot. Figure 14 shows the same EMIC waves on the 1 Hz and 5 Hz plots. The red arrow shows the EMIC wave that was shifted towards higher frequencies. Notice that the EMIC wave marked by the red arrow is not two different ones: the wave marked in the 1 Hz plot is without a doubt powerful enough to be seen in the 5 Hz plot. If the waves were different, the wave marked in the 1 Hz plot would be seen below the marked wave in the 5 Hz plot. Also notice that the other EMIC waves are not shifted: the 1/5 discrepancy was not a general occurrence but something that seemed to happen at random. The way the discrepancy was handled in the analysis is described in WAG 4.

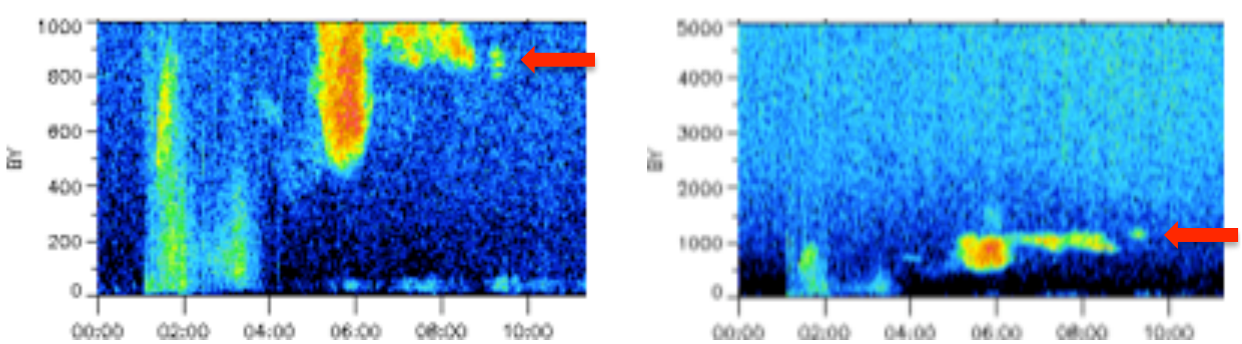

Figure 14 Example of 1/5 discrepancy. The red arrows mark the EMIC wave that was shifted towards higher frequencies in the 5 Hz plot.

The biggest issue with the data acquisition was that, despite the careful guidelines regarding EMIC wave definition, the decision of what counts as an EMIC wave and what does not was still up to the analyst's discretion. Determining what was an "easily visible amount of light green color" was not always easy, and it was difficult to stick to the exact same definition over long periods of time. Even more difficult was the segment separation, since the EMIC waves were often very overlapped. Like the definition of cut off power, the qualities that a segment had to have in order to be separated were easily changed over long periods of time. Determining where an EMIC wave starts and ends is also difficult. Many EMIC waves decrease in power near the edges, and determining max and min frequency, and start and end time, is seldom straightforward.

This anecdote describes the difficulty with data analysis well: I started the analysis with the year 2007, but when I finished the year I realized that my EMIC wave definitions had changed in the process. I started on 2007 again, but after going through about half the year I realized that I had, once again, failed to be consistent. I analyzed 2007 a third time, but when I was done I was still not convinced that I had been consistent enough in my analysis. 2007 is therefore not included in this statistical analysis.

When I started on 2008 I thought that I would be able to keep consistency throughout the analysis, and I believe that the analysis of the five-year period has been relatively consistent. However, the difficulties still remained and I recognize the fact that the analysis may not be completely consistent.

Results

The total number of EMIC waves and number of EMIC waves above 1 Hz were compiled as monthly and yearly totals, and 2008-2012 monthly totals. The percentage of EMIC waves above 1 Hz, percentage of missing data, frequency range, and duration were compiled as monthly averages. The percentage of EMIC waves above 1 Hz, percentage of missing data, min and max frequency, and frequency range were compiled as yearly averages, and also 2008-2012 monthly averages (except for min and max frequency). The results are shown in figures 15 through 21.

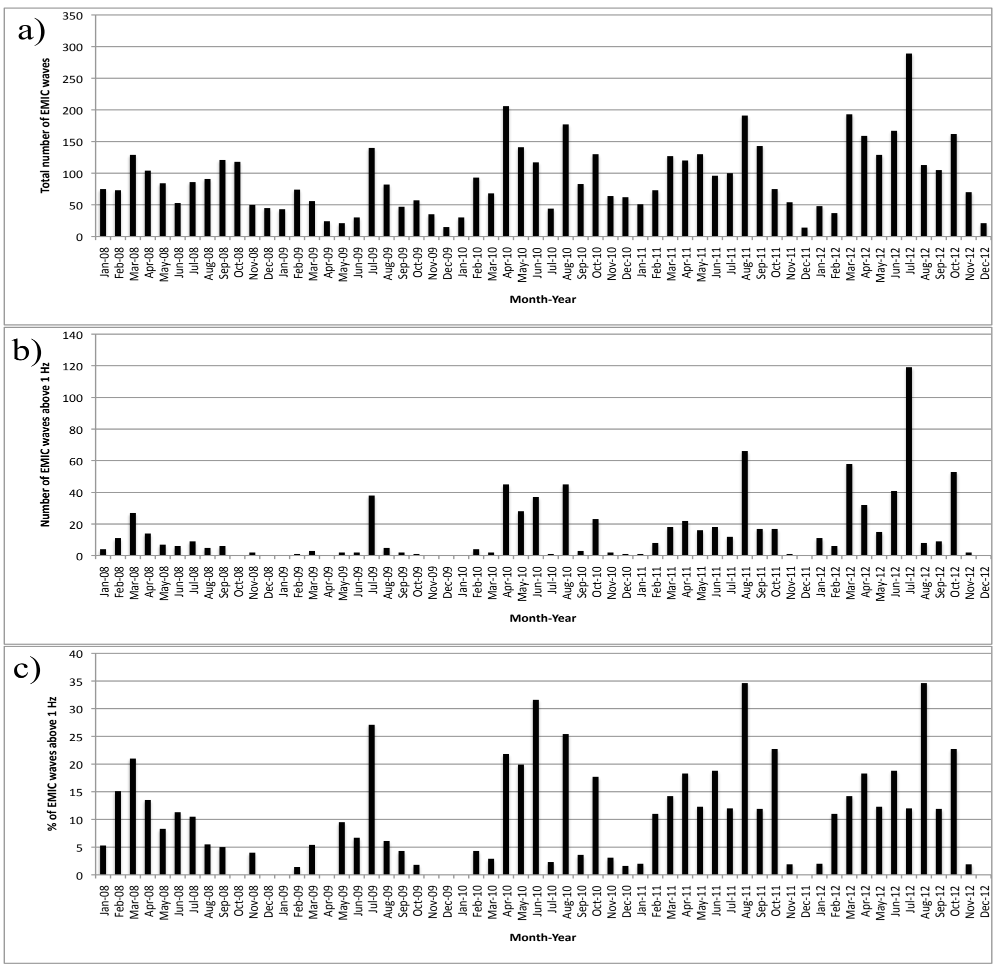

Figure 15 a) Total number of EMIC wave occurrences per month during the 5-year period. b) Number of EMIC waves above 1 Hz per month during the 5-year period. c) Percentage of EMIC waves above 1 Hz for each month during the 5-year period.

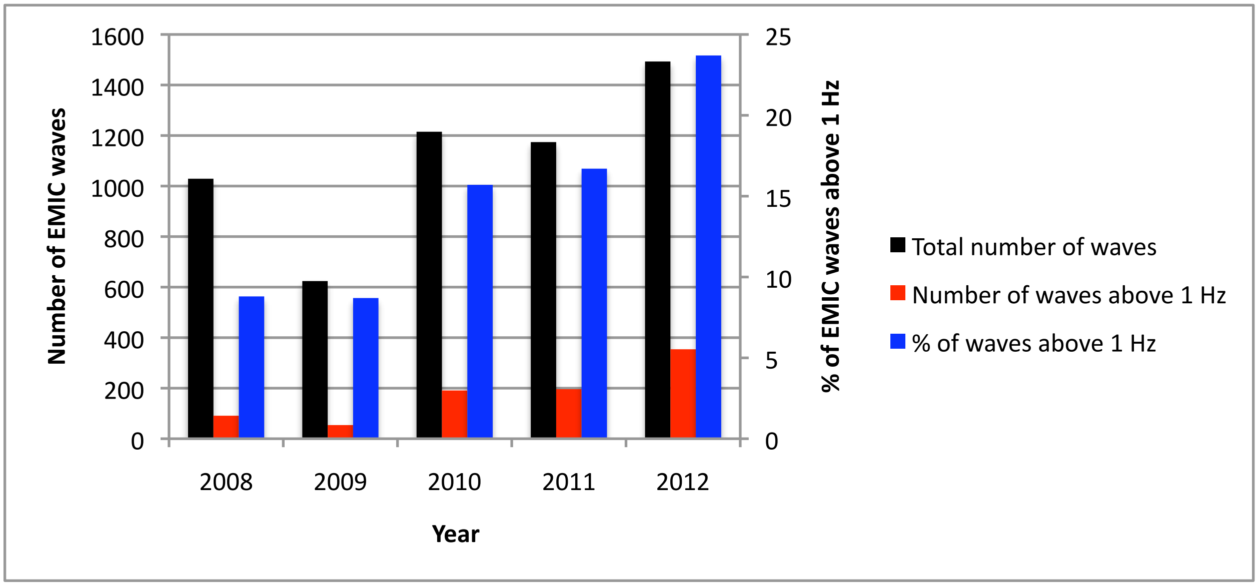

Figure 16 Total number of EMIC waves, number of EMIC waves above 1 Hz and percent of EMIC waves above 1 Hz for each year.

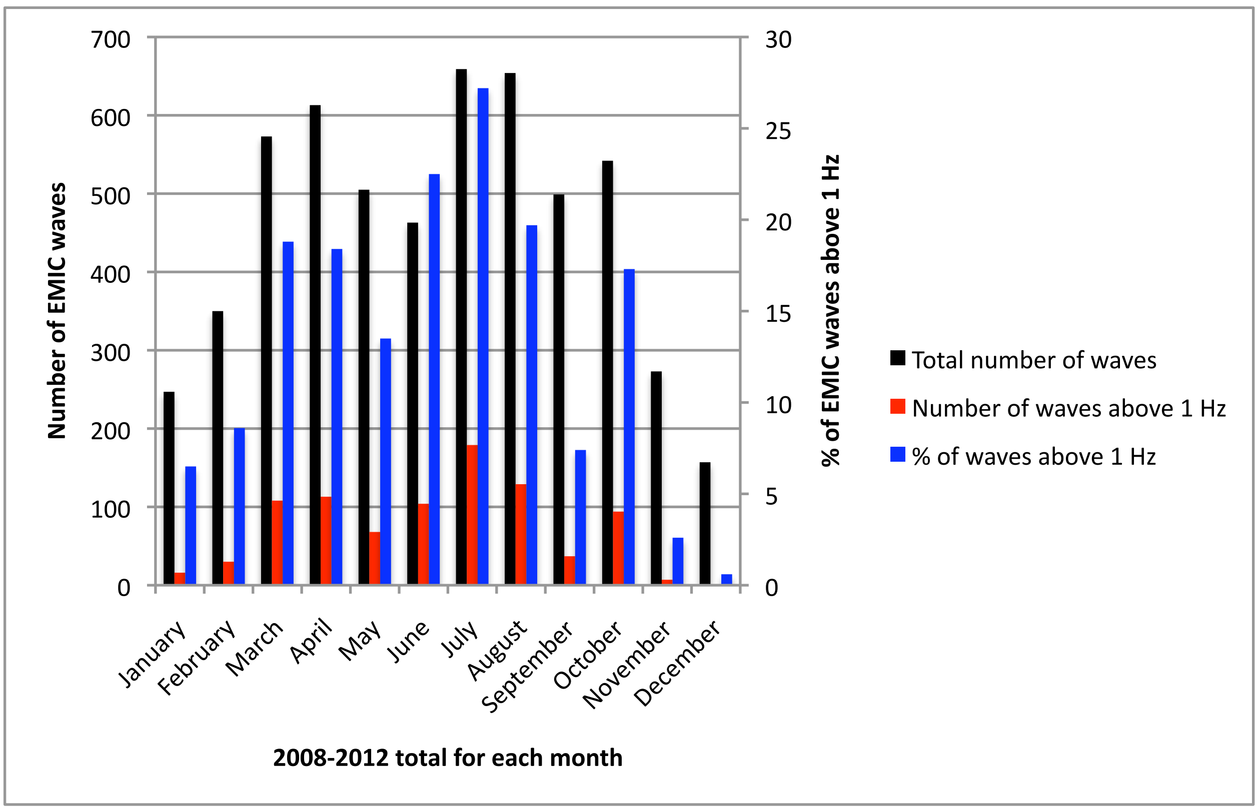

Figure 17 Total number of EMIC waves, number of EMIC waves above 1 Hz and percent of EMIC waves above 1 Hz for each month, summed over all months 2008-2012.

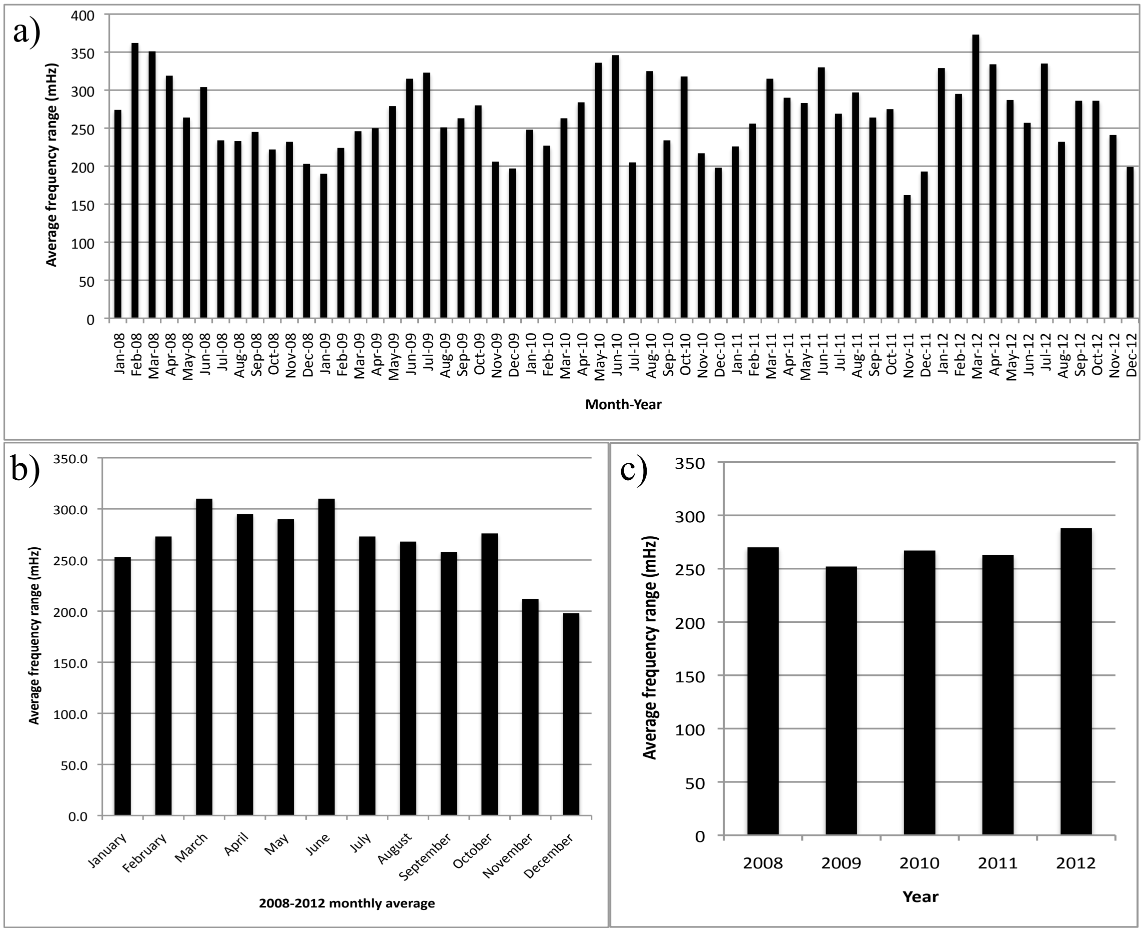

Figure 18 a) Average EMIC wave frequency range for each month during the 5-year period. b) Average EMIC wave frequency range for each month, averaged over all months. c) Average EMIC wave frequency range for each year.

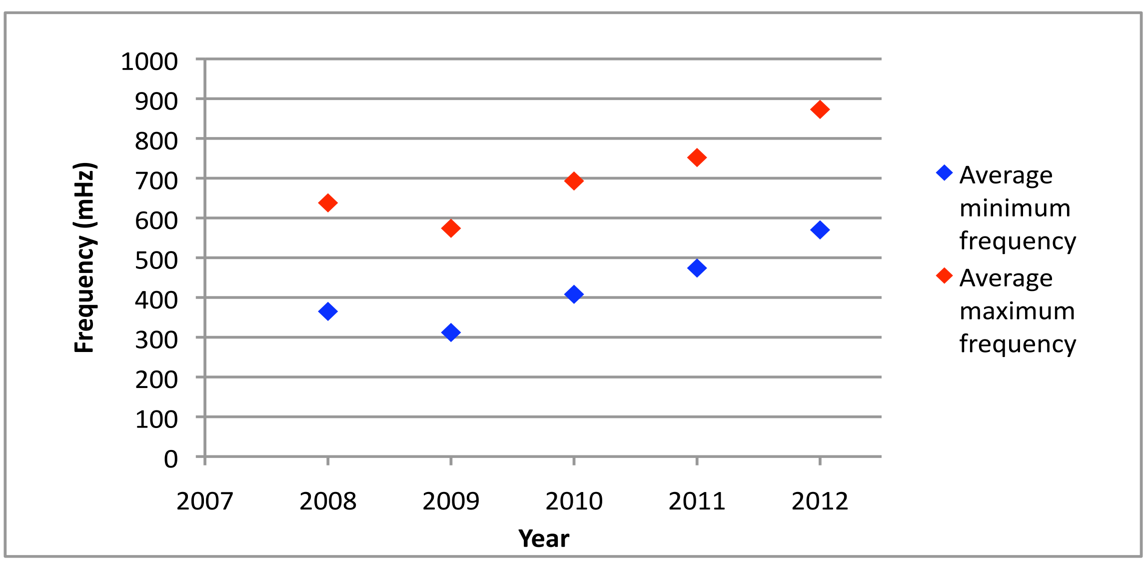

Figure 19 Average minimum and maximum EMIC wave frequency for each year.

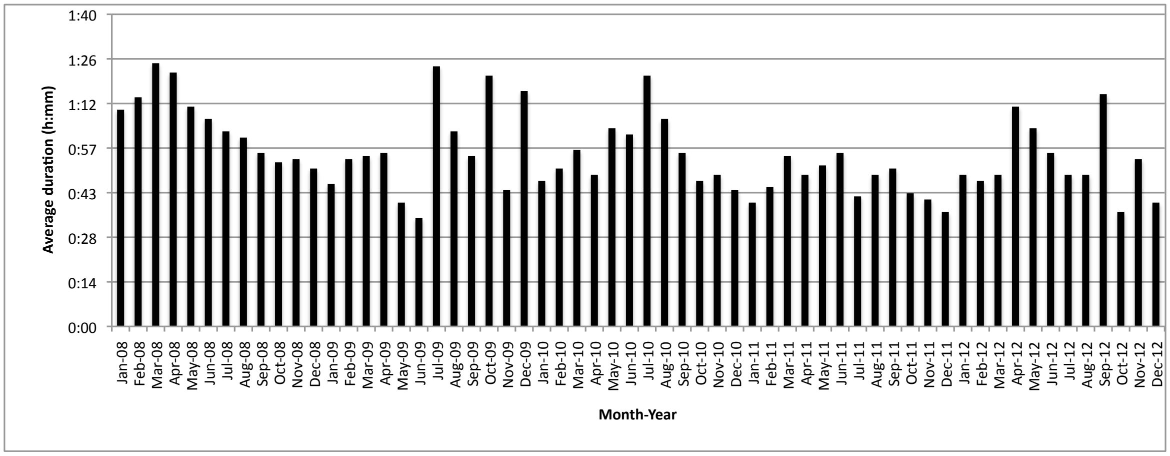

Figure 20 Average EMIC wave duration for each month during the 5-year period.

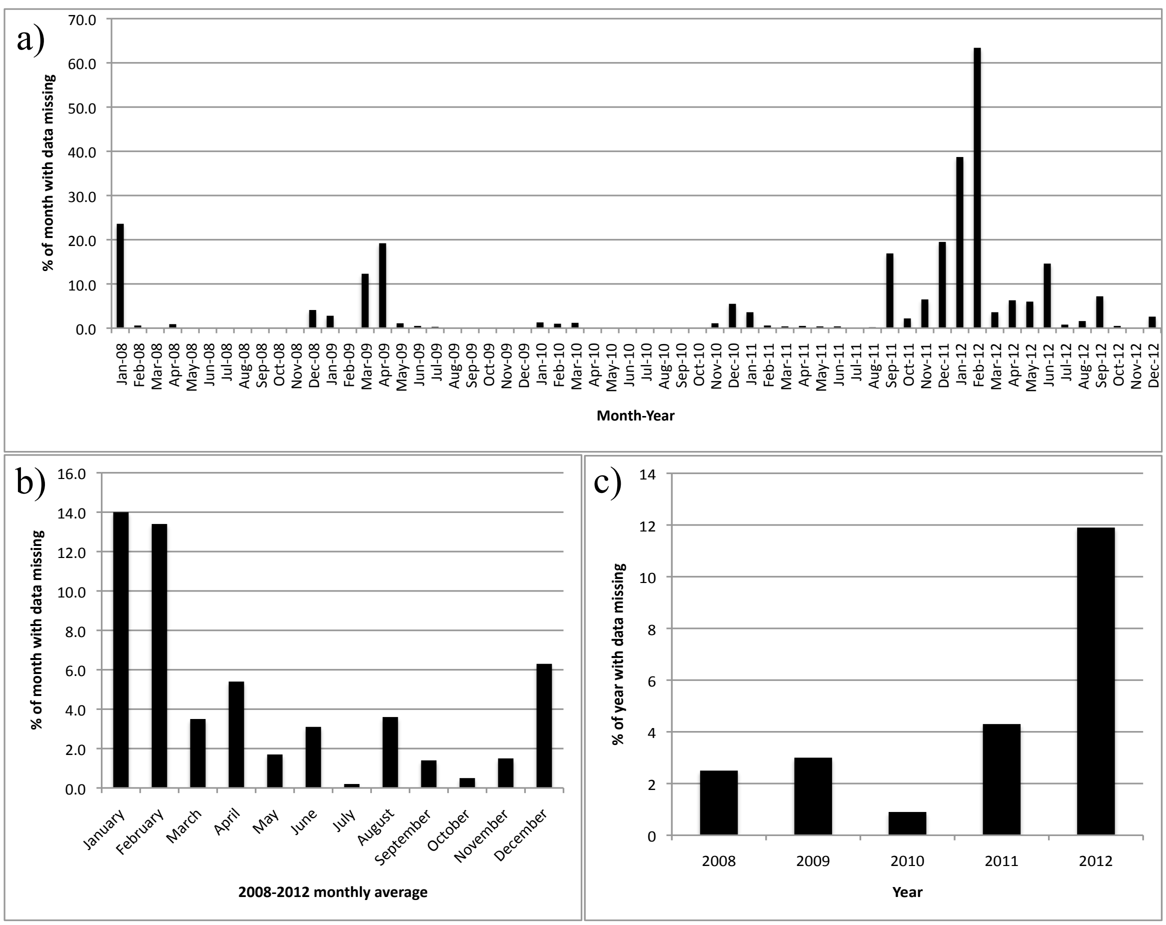

Figure 21 a) Percentage of the month with missing data, for each month during the 5-year period. b) Percentage of missing data for each month, averaged over all months. c) Percentage of missing data for each year.

Discussion

The data shows an increase in the total number of EMIC waves as well as the number and proportion of EMIC waves above 1 Hz during the 5-year period. This can be seen in figures 15 and 16. The result is most clear in figure 16: the total number of waves, the number of waves above 1 Hz and the percentage of waves above 1 Hz reached clear maxima during 2012, and minima in 2009. The percentage of waves above 1 Hz was only 0.1 percentage units lower during 2009 compared to 2008, however. The increasing trend coincides with the recent rise in solar activity [7], and the minima occurred during the solar minimum of 2009. A plot of the solar cycle as measured by sunspot count can be seen in figure 22.

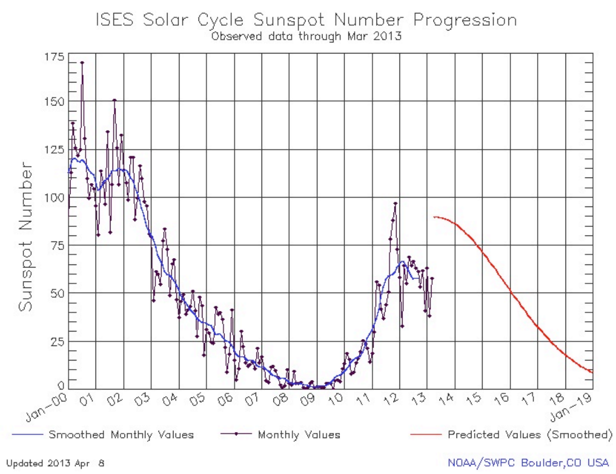

Figure 22 The 11-year solar cycle as measured by sunspot count, from the Space Weather Prediction Center.

The correlation between the solar cycle and EMIC wave occurrence contradicts the results published by Guglielmi et al., who found a correlation coefficient of $r = -0.82$ between the solar cycle and Pc1 wave occurrence during an acquisition period of 36 years. A possible explanation for this discrepancy could be that different wave definitions were used, but since Guglielmi et al. did not present any results regarding wave duration and frequency range, or their wave definitions, it is difficult to know. It is also possible that processes other that the solar cycle affect EMIC wave occurrence more strongly, and that changes in these processes caused the discrepancy. Finally, the instrumentation used at Halley may have been different than that used for collecting the data that Guglielmi et al. analyzed, something that may have influenced the results. Many EMIC waves with short duration and frequency range found by myself would be almost impossible to notice with poor instrument resolution.

The average wave frequency range was lowest in 2009 and highest in 2012 (figure 18c), but the differences are too small to draw any strong conclusions. As mentioned in the Data Acquisition section, determining where an EMIC wave starts and ends is not always easy, and margin of error when determining frequency ranges may be too large for me to determine any trends. Also, EMIC wave frequencies are determined to within 25 mHz in the 1 Hz plot and within 100 mHz in the 5 Hz plot, which means that the minimum frequency range for an EMIC wave is 25 mHz on the 1 Hz plot but 100 mHz on the 5 Hz plot. This means that a year containing more EMIC waves above 1 Hz will most likely have larger average frequency ranges than a year with few EMIC waves above 1 Hz. However, it is interesting that the lowest average frequency range was found in 2009 while the highest average frequency range was found in 2012, since the solar activity as measured by sunspot count was lowest in 2009 and highest in 2012.

Figure 19 shows the average minimum and maximum frequencies for each of the five years. The difference in average min and max frequency from year to year is very clear, but the figure does not show any big differences in average frequency range. Together with figure 18c, figure 19 shows that the frequency range of the average EMIC wave has remained roughly the same during the 5-year period, but that the min and max frequencies of the average wave were lowest in 2009 and highest in 2012. In other words: the increase in number and percentage of EMIC waves above 1 Hz does not seem to be a result of an increase in EMIC wave frequency range, which would enable a typical wave to cover a larger range of frequencies; but a result of the fact that the average EMIC wave has shifted towards higher frequencies during the 5-year period, with the lowest average min and max frequencies in 2009 and highest min and max frequencies in 2012.

Figure 20 shows the average EMIC wave duration for each month during the 5-year period. The average wave duration seems longest in 2008, but once again I am reluctant to draw any conclusions. EMIC wave duration is even more difficult to determine than EMIC wave frequency range, and it is possible that the way wave duration was determined changed during the acquisition process. Therefore, I did not compile the average EMIC wave duration data by month and year; I think that the margin of error is too large to draw any definite conclusions.

All data seem to suggest a seasonal dependence in EMIC waves. Figures 15 and 16 show that the total number of EMIC waves as well as number and proportion of EMIC waves above 1 Hz reach minima during the austral summer. The frequency range data also shows minima during the summer months, especially during November and December. This can be seen in figures 18a and 18b. The average wave duration also seems to reach minima during the summer months, although the trend is less clear. The summer minima suggest that a sunlit ionosphere attenuates wave transmission through the ionosphere.

Figure 21a shows the percentage missing data for each month during the 5-year period. January and February 2012 were missing a lot of data, and that is probably the reason for the low wave counts for those two months (figure 15a). As can be seen in figure 21b, the average of percentages of missing data for January and February were higher than the rest for the acquisition period as a whole. However, the amount of missing data is not large enough to explain the minima in EMIC wave occurrence during those months. Figure 21c shows the percentage of missing data per year. Even though 2012 was missing most data by far, the year also had the most EMIC waves both in total number and number above 1 Hz. This strengthens the evidence suggesting an increase in the number of EMIC waves during 2012.

After the analysis was done, I considered it a questionable decision to introduce a cut off power. The cut off power was introduced because low-powered EMIC waves could easily be lost in noise, and by setting a cut off power I made sure that what I counted as EMIC waves didn't get lost during long segments of low-powered noise. This decreased the effect of noise on data acquisition. However, most noise is powerful enough to cover all but the most powerful EMIC waves, and many clear EMIC waves were not counted because they were below cut off power. Clear EMIC waves below cut off power seemed to be more common during November and December, which could explain the low counts of waves during those months, at least to a certain extent. The results would have been different if not for the cut off power, but I do not think that the quantitative results would have changed: not even the seasonal dependence. The percentage of events above 1 Hz would almost certainly have dropped since almost all EMIC waves below cut off power are below 1 Hz.

Conclusions

The 5-year time period of 2008 through 2012 showed an increase in the total number of EMIC waves as well as the number and percentage of EMIC waves above 1 Hz, reaching maxima in 2012 and minima in 2009. The minimum in percentage of waves above 1 Hz was barely distinguishable from the 2008 percentage, however. The increase coincided with the recent rise in solar activity, and the minima coincided with the solar minimum of 2009. The correlation between EMIC wave occurrence and the solar cycle contradicts previously published results.

The average EMIC wave frequency range was lowest in 2009 and highest in 2012, but the changes were too small to be considered trends. While the difference in frequency range between the years were small, the average minimum and maximum frequencies were lowest in 2009 and highest in 2012. This suggests that the average EMIC wave shifted towards higher frequencies, reaching maxima in 2012 and minima in 2009.

The average EMIC wave duration seems to be longest during 2008, but the margin of error in those measurements is large and no definite conclusions regarding long-term trends in average wave duration can be drawn.

The EMIC waves show a seasonal dependence, with minima for total number of waves, number and percentage of waves above 1 Hz, average wave frequency range and average wave duration during the austral summer months. The minima are especially clear during November and December. The data suggests that a sunlit ionosphere attenuates wave transmission through the ionosphere.

Future Perspective

A good start in continuing the work I have presented would be to go back further than 2008, and to analyze 2013 when the year is over. If EMIC wave occurrence and frequency really is connected to the solar cycle, 2007 and 2006 should have higher total number of waves as well as number and percentage of waves above 1 Hz than 2008, and by extension, 2009. 2006 should be more active than 2007. 2013 should at least be more active than 2009.

It would be beneficial to go over 2008 through 2012 again, and include waves that were below cut off power. As mentioned in the Discussion, the decision to introduce a cut off power was a questionable one. When going over the 5-year period again, it would be wise to review my data. I mentioned in the Data Acquisition section that I cannot guarantee complete consistency throughout the 5-year period, and discrepancies between the guidelines and my results may exist.

If possible, it would be interesting to introduce some kind of power-rating system for the analysis. Segments of EMIC waves are usually powerful, and the EMIC waves during days with numerous waves are often very powerful. There is definitely a difference in power during the seasons, with low-powered events being more common during the austral summer months. A power-rating system could provide further evidence for a seasonal dependence of EMIC waves.

More generally, it would be interesting to connect the results of this study to something more specific than the 11-year solar cycle. Comparing the results to Coronal Mass Ejections, solar flares or geomagnetic storms might yield more insight into how exactly EMIC waves relate to Sun-Earth interactions. Finally, it would be interesting to investigate what mechanisms cause the summer minima that can be seen in all EMIC wave characteristics. The seasonal dependence was one of the strongest trends in the analysis, and it is an intriguing correlation.

References

1. Kozyra, J. A.; Cravens, T. E.; Nagy, A. F.; Fontheim, E. G.; Ong, R. S. B. "Effects of energetic heavy ions on electromagnetic ion cyclotron wave generation in the plasmapause region" *J. Geophys. Res.* **89**, 2217 (1984).
2. Fraser, B. J.; Loto'Aniu, T. M.; Singer, H. J. "Electromagnetic ion cyclotron waves in the magnetosphere" *Magnetospheric ULF waves: Synthesis and New Directions* **169**, 195-212 (2006).
3. *PSD Data Access Framework, Sun-Earth Interactions, SCM.* British Antarctic Survey, 2006. Web. 1 May 2013.
4. *Magnetosphere-Ionosphere Research Lab*, Institute for the Study of Earth, Oceans, and Space, n.d. Web. 3 May 2013.
5. Roscoe, H. K.; Colwell, S. R.; Shanklin, J.D.; Karhu, J. A.; Taalas, P.; Gil, M.; Yela, M.; Rodriguez, S.; Rafanelli, C. R.; Cazeneuve, H.; Villanueva, C. A.; Ginsburg, M.; Diaz, S.B.; de Zafra, R. L.; Muscari, G.; Redaelli, G.; Dragani, R. "Measurements from ground and balloons during APE-GAIA – A polar ozone library" *Advances in Space Research* **36**, 835-845 (2005).
6. Guglielmi, A.; Potapov, A.; Matveyeva, E.; Polyushkina, T.; Kangas, J. "Temporal and spatial characteristics of Pc1 geomagnetic pulsations" *Advances in Space Research* **38**, 1572-1575 (2006).
7. *Solar Cycle Progression,* Space Weather Prediction Center, 8 April 2013. Web. 22 April 2013.