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Observed Variations in HF Propagation Over A Path Aligned Along the Mid-Latitude Trough

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Abstract: *This work presents observations from an extensive set of measurements of the direction of arrival and signal strength of HF signals propagating on a path (Ottawa to Bruntingthorpe) oriented along the mid-latitude trough with path length 5254km. Signals were radiated on five frequencies between 5.4 and 14.4 MHz and measurements span the period from the 2009 sunspot minimum to July 2014, which is within the present sunspot maximum. Deviations were observed to occur from 7 to 14.4 MHz. The largest deviationswere mostly southerly and occurred at the highestfrequencies:8, 11.1 and 14.4 MHz. In general, deviations occurred more in winter than summer. The received signal strengths were greater during summer than winter and the largest signal strengths were produced at the lowest frequency while the largest frequency produced the least signal strengths. There is also an observed effect on the duration and percentage of occurrence of propagation due to the solar cycle.*

Keywords:*HF propagation, Mid-latitude trough, Hourly variations, Seasonal variations, Sunspot cycles, Ottawa, Bruntingthorpe.*

I. Introduction

High-Frequency (HF) radio propagation is made possible through refraction by the ionosphere, and the ionosphere is that part of the atmosphere in which free electrons are sufficiently numerous to influence the propagation of radio waves. The name ionosphere comes from the fact that this region is formed by the ionization of atoms in the atmosphere thereby creating free electrons. These free electrons in the ionosphere cause HF radio waves to be refracted and eventually directed back to earth [1]. It goes on to say that the greater the density of electrons, the higher the frequencies that can be reflected. According to this same source, the ionosphere may have four regions present during the day. These regions are called the D, E, F1 and F2 regions.

Their approximate height ranges are:
- D region 50 to 90 km;
- E region 90 to 140 km;
- F1 region 140 to 210 km;
- F2 region over 210 km.

At certain times during the solar cycle the F1 region may not be distinct from the F2 region with the two merging to form an F region. At night the D, E and F1 regions become very much depleted of free electrons, leaving only the F2 region available for communications [1].

These varying characteristics of the ionosphere with respect to time of day, seasons, and solar cycles, make HF prediction and propagation a somewhat difficult task. According to Merriam-Webstar online dictionary, the mid-latitudes are latitudes of the temperate zones or from about 30 to 60 degrees north or south of the equator. Located within the mid-latitudes is the trough which according to [2], is a major feature of the F-region ionosphere that forms at the boundary between the mid-latitudes and auroral ionospheres, and where the plasma concentration is usually lower compared with regions immediately poleward and equatorward. In terms of time of formation/appearance, the local time extent of the trough is small in summer, centred about midnight, and extends further towards dawn and dusk with progression towards winter [2]. For terrestrial HF radio systems, the electron depletion in the trough region reduces the maximum frequency that can be reflected by the ionosphere along the great circle path (GCP) [3]. Also, in the mid-latitudes, this electron density depletion and subsequent reduction in maximum useable frequency (MUF) often leads to large deviations from GCP [4]. A signal however, can still be reflected from the gradients in the poleward and equatorward walls of the trough or scattered from irregularities embedded in the trough or in the auroral region which lies just poleward of the trough [5]. In [6], it was also affirmed that these reflections from gradients and irregularities in the trough caused the signals to arrive from directions away from the GCP and at times delayed with respect to normal propagation.

Having taken measurements during sunspot maximum in 2001 for a shorter trough path between Uppsala, Sweden and Leicester, it was observed in [7] that the off-GCP signal received (deviations) were majorly to the north, with southerly deviations being much less frequent. These results they however reported were in contrast to a similar experiment conducted near sunspot minimum in 1994 in Canada, during which both southerly and northerly deviations were observed in the 5-15 MHz range, showing variations in DOA with respect to solar activity. In [8] deviations were found to occur more often at night especially during the winter and equinoctial months for signal frequencies between 7 and 11.1 MHz and these deviations were large.

Deviations in direction of arrival (DOA) due to the presence of the trough is not only an issue in radio communication systems where directional antennas are employed but also impacts greatly on radiolocation systems for which estimates of a transmitter location are obtained by triangulation from a number of receiving sites [8]. This could cause wrong assumptions for transmitter position, leading to timing and positional errors in navigation systems such as GPS.

This work aims to investigate the effects of the mid-latitude trough on signals transmitted within the mid-latitudes by analyzing HF transmissions from Ottawa, Canada (45.42N, 75.7W) to Bruntingthorpe, Leicester, (52.49N, 1.11W) with a path length of 5254km. This work will give HF radio engineers an insight on the behaviour of signals transmitted during winter over this trough path and also see how these effects change with frequency and with solar cycle, thus enabling proper planning and execution of reliable and efficient communications.

II. Materials And Method

A. Materials

Data obtained from measurements between the trough path (Ottawa to Bruntingthorpe) were collected over the duration spanning the recent solar minimum (2011) to the present (2014) which is within the present solar maximum. These data which contain the received signal strength and direction of arrival were obtained for each year. In each year, the peak month in winterand summer was chosen to represent the winterand summer seasons respectively. A 10-day transmission data for the chosen months was then used for the analysis.

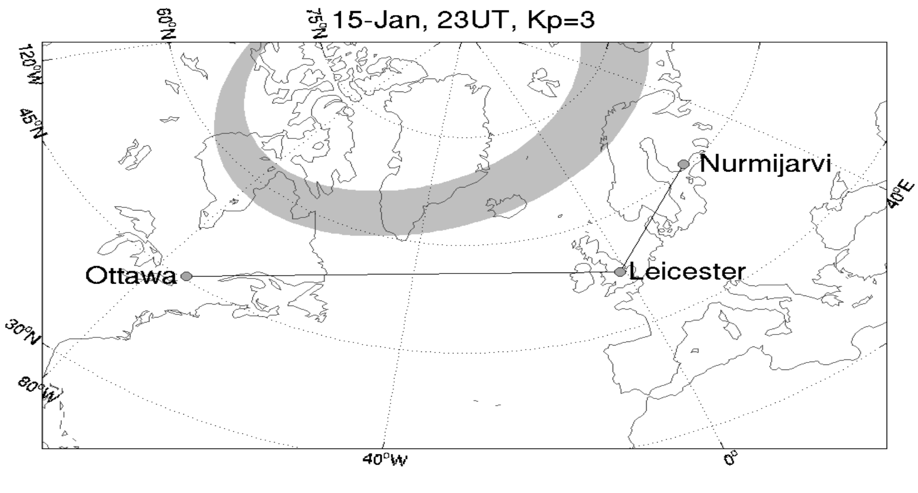

Figure 1: Map showing the paths employed in the reported measurements, withgeographical coordinates.

B. Method

The method used to make the measurements has been discussed in detail elsewhere in [7] and [9], and the days for which measurements were made is given later in this section.

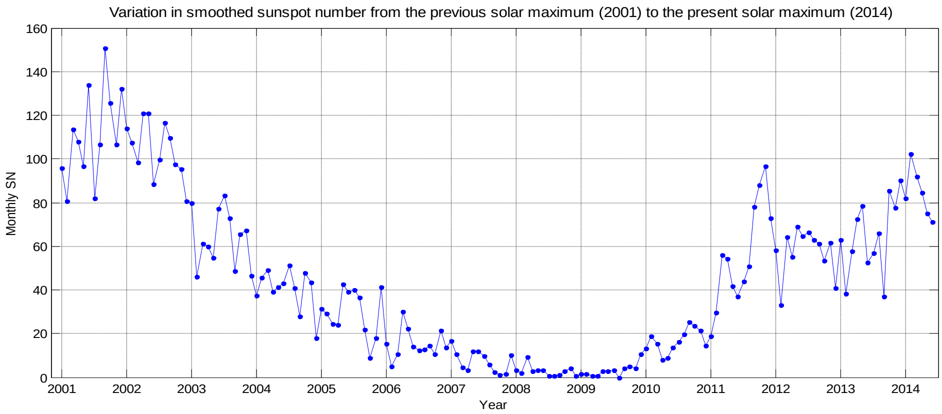

Figure 2: Variation in smoothed sunspot number over a solar cycle. The quantity plotted is the monthly mean international sunspot number downloaded from the Space Weather Prediction Centre, US National Oceanic and Atmospheric Administration in [10].

In deriving the statistics presented in Figs 3a-e and Tables 1 and 2 of this work, propagation is deemed to have occurred if any readily identifiable trace, other than sporadic E, is seen between 00:00-24:00 UT. The sporadic E is a region which is very unpredictable in its time of formation, the area which it covers, the duration for which it persists, and even in its electron density. For this reason it was excluded, so as to eliminate any short-lived reflections.

All strong off-GCP propagation was considered as true reflections whether or not it occurred for up to 50% of the days observed (5 days). Weak off-GCP propagation that occurred for up to 50% of days observed was regarded as possible reflections but only the days with strong reflections were included whereas weak off-GCP propagation that did not occur for up to 50% of the days observed were excluded. During some intervals however, the data quality was not sufficient to categorise the direction of arrival and these together with the short-lived deviations that sometimes occur briefly at dawn and dusk, have been excluded.

The total percentage for each mode (GCP, northerly, or southerly deviations) should equal 100% which would indicate that that particular mode existed for 24 hours on all 10 days investigated (i.e. 240 hours) for each season considered.

Finally, for frequencies where there was more than one northerly or southerly reflection (e.g. for 8 MHz in winter of 2012, where there exists two northerly deviations: 10°N and 20°N and three southerly deviations: 10°S, 30°S and 140°S), the combination of the highest counts for each hour of the day derived from both/all modes as the case may be, was used in computing the percentages presented in Table 2. This is because the figures presented are only meant to show the times of day during which deviations occurred (regardless of the degree of deviation and number of deviations for each mode), so as to enable the prediction of which modes supported or dominated propagation at various times of the day

Given below are the days for which measurements were made and used for the analysis in this work.

- 2011: January 01-6 and 20-23, July 5-14
- 2012: January 19-28, July 20-29
- 2013: January 3-12, July 19-28
- 2014: January 7-16, June 20-29

III. Results

Results are presented from a solar minimum to the present solar maximum to observe any perceived variations.

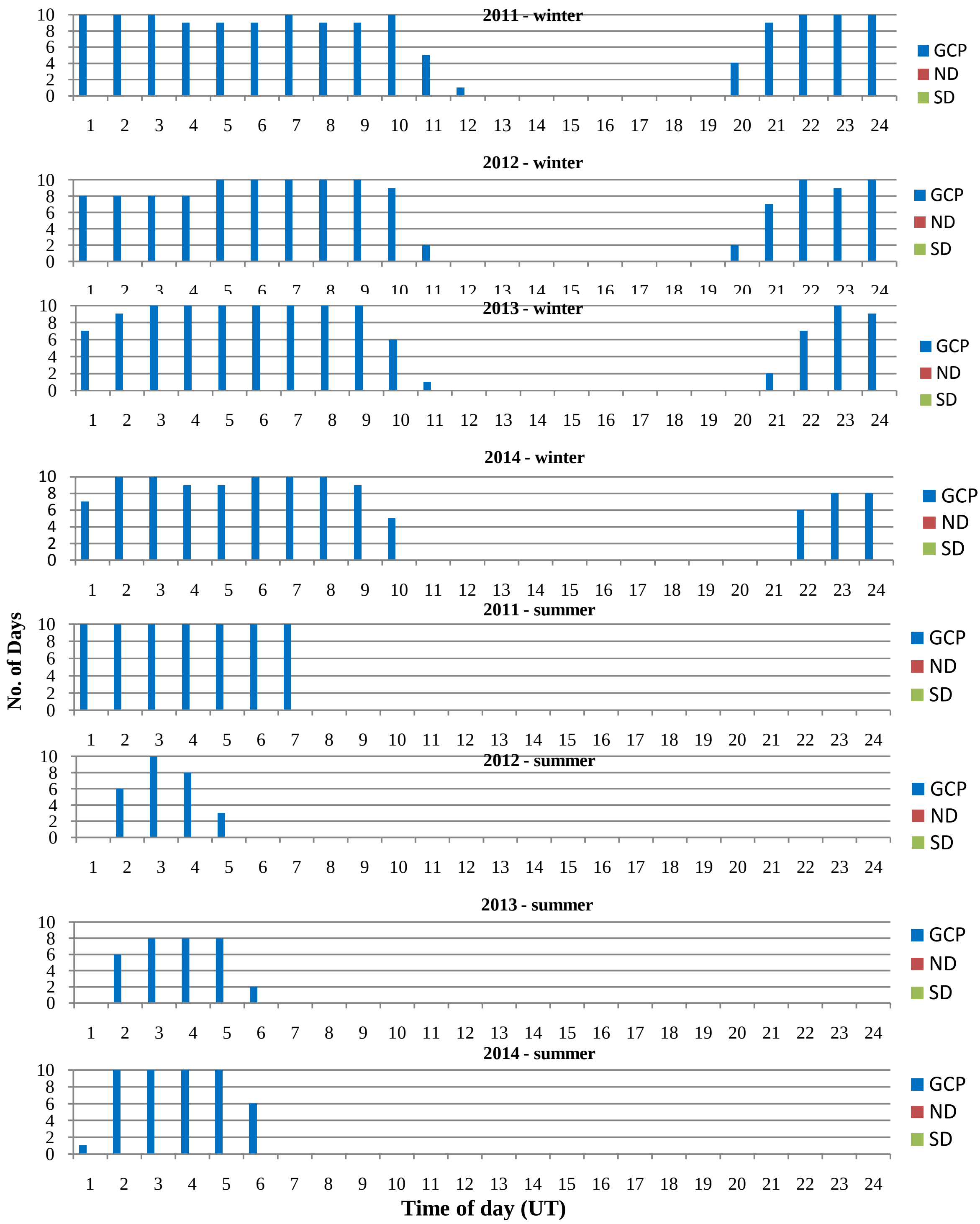

Figure 3a: A plot of hourly and yearly occurrence of propagation at 5.4 MHz (winter and summer)

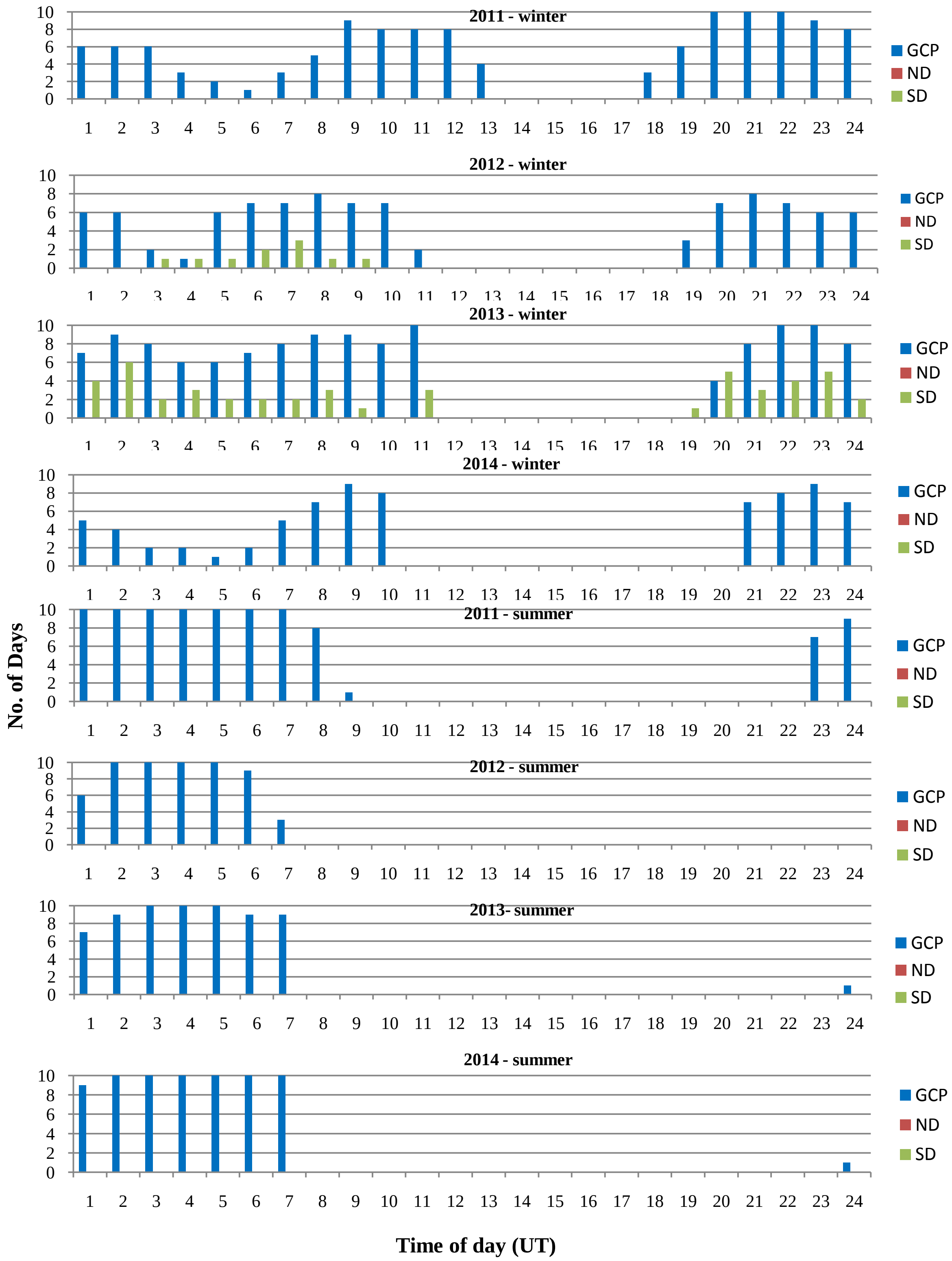

Figure 3b: A plot of hourly and yearly occurrence of propagation at 7 MHz (winter and summer)

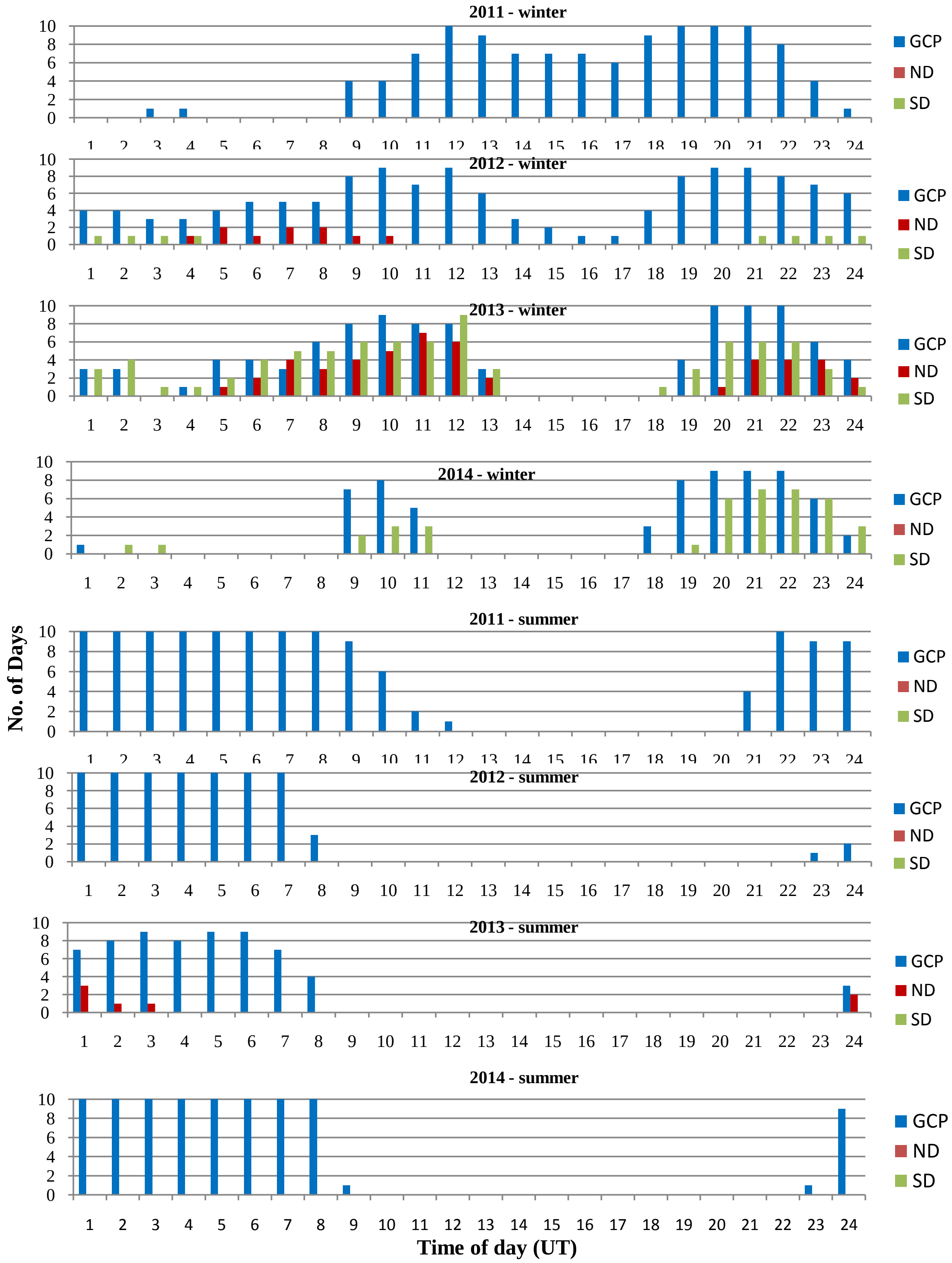

Figure 3c: A plot of hourly and yearly occurrence of propagation at 8 MHz (winter and summer)

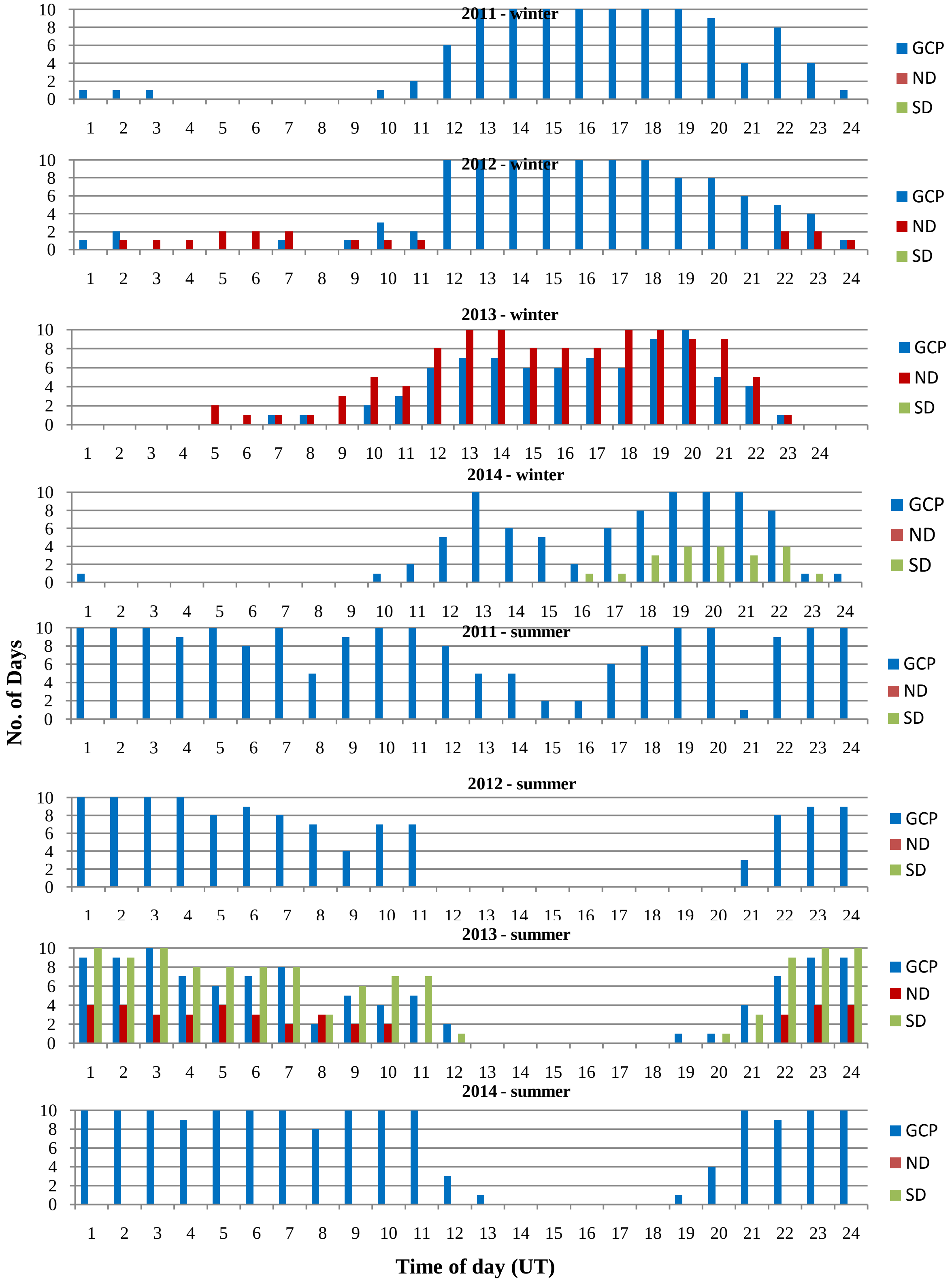

Figure 3d: A plot of hourly and yearly occurrence of propagation at 11.1 MHz (winter and summer)

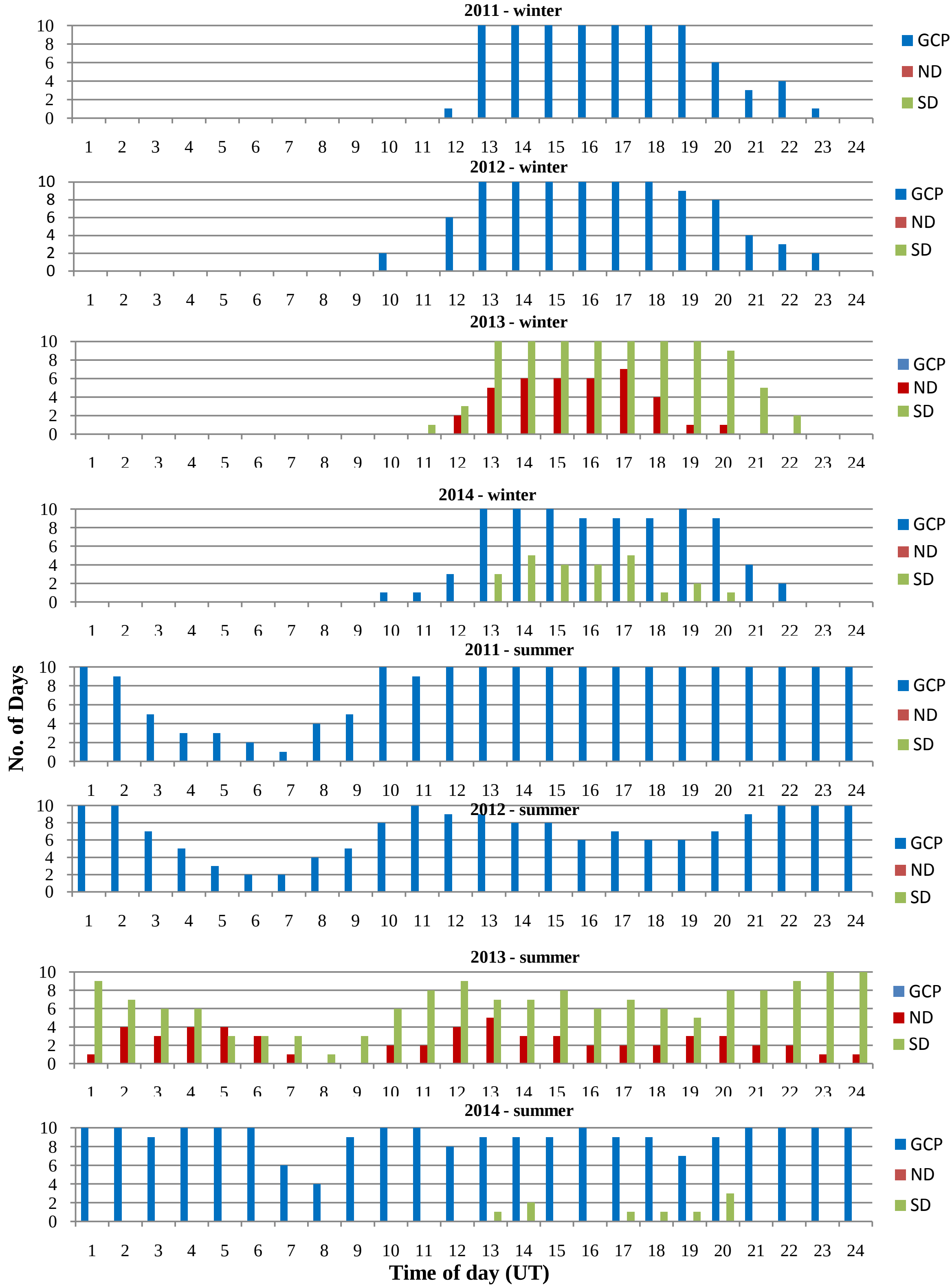

Figure 3e: A plot of hourly and yearly occurrence of propagation at 14.4 MHz (winter and summer)

IV. Observations And Discussions

A. GCP Propagation

During winter at 5.4 MHz, GCP propagation exists mainly from 20:00 UT extending into midnight and up to midday the following day. This duration of existence tends to decrease gradually as solar activity increases, thus reducing in duration to 22:00 UT at night till 10:00 UT the following morning in 2014. At 7 MHz, the same trend with respect to GCP propagation duration and solar activity is observed and this is similar to observations made during winter at a low frequency,for a shorter trough path in [13]. At 7 MHz however, GCP propagation exists mainly from 18:00 UT (around dusk) up to 13:00 UT the following day, decreasing in duration to 21:00 UT to 10:00 UT the following day, as solar activity increases. For each year, as frequency increases, there is a gradual interchange between periods of GCP propagation and periods of no-GCP propagation. This can be observed by looking simultaneously throughFigs 3a to 3e for each year. Looking at winter of 2011 at 5.4 MHz, GCP propagation exists from 20:00 to 12:00 noon the following day, with no GCP propagation from 1:00 UT to 19:00 UT. However, for the same year but at 14.4 MHz, GCP mode exists from 12:00 noon to 23:00 UT while the rest of the day experiences no GCP propagation.

For summertime at 5.4 MHz, GCP propagation exists mainly just after midnight from 01:00 UT to 07:00 UT and tends to decrease as solar activity increases. A similar trend with respect to GCP propagation and solar activity is observed at 7 MHz and 8MHz, though not very obvious as in 5.4 MHz. Similar to the short trough path in [13], GCP propagation is stronger in winter than in summer for daytime (seasonal/winter anomaly). This winter anomaly is however not consistent above 8 MHz. Just as observed in [13], an increase in frequency was accompanied by a gradual increase in duration of GCP propagation throughout the whole day for each year. This can be noticed by observing the duration of GCP propagation for each year across all frequencies of transmission, using Figs3a-3e.

B.Observed Deviations

Table 1: Observed seasonal and yearly deviations at various frequencies

OBSERVATIONS Path: Ottawa-Bruntingthorpe			
Time of year	**Frequency (MHz)**	**Northerly Deviations (°n)**	**Southerly Deviations (°s)**
2012			
Winter	**7**		110
	8	10,20	10,30,140
	11.1	10,20	
2013			
Winter	**7**		80
	8	30	70,100
	11.1	15	
	14.4	10	100
Summer	**8**	30	
	11.1	10	70,110,150
	14.4	110	60,100
2014			
Winter	**8**		120
	11.1		90
	14.4		120
Summer	**14.4**		150

Table 1 shows the observed deviations and their magnitude over the period of observation. It shows that deviations from the GCP occurred both northerly and southerly. Generally, larger deviations occurred mostly southwards of the GCP. Despite these deviations, propagation was usually dominated by the GCP.

All figures in Table 2 have been rounded-up or down to the nearest whole number in other to avoid ambiguity. The figures under the "No Propagation" sub-column are obtained by subtracting the highest occurrence percentage on corresponding sub-columns under GCP, Northerly deviations, and Southerly deviations from 25%, which is the maximum percentage per sub column, making a total of 100% per column.

Table 2: Percentage Occurrence Statistics by Mode and Bearing for Signal Frequencies of 5.4, 7.0, 8.0, 11.1, and 14.4 MHz

Time of year	Freq (MHz)	OBSERVATIONS Path: Ottawa-Bruntingthorpe															
		No propagation				GCP (UT)				Northerly Deviations (UT)				Southerly Deviations (UT)			
		4-9	10-15	16-21	22-3	4-9	10-15	16-21	22-3	4-9	10-15	16-21	22-3	4-9	10-15	16-21	22-3
2012																	
Winter	7	13	18	17	11	12	7	8	14	0	0	0	0	4	0	0	0
	8	12	10	12	12	13	15	13	13	4	0	0	0	0	0	0	3
	11.1	22	6	3	10	1	19	22	5	3	1	0	3	0	0	0	0
2013																	
Winter	7	6	17	10	3	19	8	5	22	0	0	0	0	5	2	4	10
	8	14	13	15	14	11	12	10	11	6	8	2	5	10	10	7	8
	11.1	22	6	2	22	1	13	18	2	3	19	23	3	0	0	0	0
	14.4	25	11	2	24	0	0	0	0	0	8	8	0	0	14	23	1
Summer	8	10	0	0	14	15	0	0	11	0	0	0	3	0	0	0	0
	11.1	8	19	22	1	15	5	3	22	8	2	0	10	17	6	2	24
	14.4	17	6	8	4	0	0	0	0	5	8	6	5	8	19	17	21
2014																	
Winter	8	22	20	13	17	3	5	12	8	0	0	0	0	1	3	6	8
	11.1	25	13	6	20	0	12	19	5	0	0	0	0	0	0	7	2
	14.4	25	10	4	24	0	15	21	1	0	0	0	0	0	5	5	0
Summer	14.4	5	2	2	0	20	23	23	25	0	1	3	0	0	0	0	0

Variation with Frequency and Time of occurrence

Deviations were observed from 7 MHz and above, unlike in the short trough path in [11] and [13] were deviations began at as low as 4 MHz. Similar to the short path, the magnitude of deviations were strongest and most frequent at the higher frequencies (8, 11.1, and 14.4 MHz, in this case).Table 2 shows that off-GCP propagation was existent all through the day, occurring mostly during winter.

C.Signal Strength

For both summer and winter, no distinct mode was seen at 5.4 and 7 MHz throughout the duration of measurement (2011-2014). At 8, 11.1, and 14.4 MHz, traces of 2, 3 modes were observed to occur occasionally between 12:00 and 18:00 UT.

Another interesting feature is the higher SNRs signals produced compared to those observed in [11] and [13]. According to [12], single-hop propagation is not possible via the F2 layer for distances greater than 4000 km. This path length exceeds 4000km, hence it is expected that propagation will only be supported via a 2F2 mode or higher, thus causing the signal to traverse the D-layer at least four times and as a result more absorption, which leads to weaker signal strengths at receiver. This expected low SNRs was not the case however, as signals with SNR values as high as 24 dB and 27 dB were obtained during winter and summer respectively. These SNR values are relatively high compared to 12 dB and 15 dB obtainedin [13] and [11] for winter and summer respectively. Just as observed in the [11] and [13], this peak SNR values decreased as frequency increased, falling to 22 and 23 dB for winter and summer respectively.

V. Conclusion

Deviations occurred from 7 to 14.4 MHz between 2012 and 2014. At 5.4 MHz, GCP propagation occurred mainly between 22:00 UT to 10:00 UT the following day. As frequency increases for each year, there was a gradual interchange between periods of GCP propagation and periods of no-GCP propagation. For 5.4 and 7 MHz central frequencies, it was found that the duration of GCP propagation reduces with increasing solar activity. Just like in [13], winter anomaly was not consistent at frequencies above 8 MHz. During summer, it is found that increase in frequency improves GCP propagation, for all years considered.

The largest deviationswere mostly southerly, and occurred at the highestfrequencies**:** 8, 11.1 and 14.4 MHz. These southerly deviations increased in magnitude with increase in solar activity for each central frequency. In general, deviations occurred more in winter than in summer, confirming the assertions made in [2] about the local time extent of the trough (which is known to be the cause these deviations). Also, the received signal strengths were greater during summer than winter. Finally, for both seasons, the largest signal strengths were produced at the lowest frequency while the largest frequency produced the least signal strengths.

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