Temporal and Spatial Variation of Meteor Flux in Radio Data

Charles Powell[1,2,3] *and Kristina Veljković*[4]

The variation of hourly detection counts from almost 350 radio meteor detection stations is analysed to determine the effect of year, time of day, and latitude on observations, as well as discussions of annual and monthly variations. Results indicate a significant increase in hourly detection counts in 2009–2010, supporting previous hypotheses of correlation between radio meteor detection rates and solar activity. Annual increases in meteor rates during summer months are noted, with no clear explanation. Monthly variations are not significant. The effect of latitude on detection counts is significant for years 2005–2016. For 12 of 17 considered years, night-time detection counts are greater than day-time counts, likely due to changes in ionospheric structure at night.

Received 2017 September 6

1 Introduction

Many patterns arise in meteor detection: for example diurnal variations in meteor flux, or meteor showers which cause variation in activity rates. These trends often occur periodically, and studies of temporal variation help to study the mechanisms that cause these trends. In pursuit of this, the variation of radio meteor detection results is analysed over a daily, monthly, and annual scale. Influences of the time of day and latitude are also considered. This analysis is made using a database of hourly detection counts, provided by the Radio Meteor Observation Bulletin (RMOB)[a].

Lindblad (1968) analyses long-term variation in meteor radar rates, as well as echo amplitudes. Echo amplitudes are seen to correlate with electron line density, indicating an influence from the solar wind. It is also observed that long-term variation in radio meteor detection count can be explained qualitatively by a variation in atmospheric electron density in the region where most meteors burn up, which itself is related to the solar cycle.

Bumba (1949) calculates the yearly rate of meteors as a function of the position of the Sun in the solar cycle, demonstrating an inverse relationship between solar activity and detection counts.

Singer et al. (2005) note an increasing diurnal rate with decreasing latitude, suggesting that overall, hourly detection counts increase with lower latitudes. A greater meteor flux in summer (for the Northern Hemisphere) is noted.

2 Method

2.1 Data collection

Table 1 – Number of observers by latitude class.

Latitude class (°)	N^o observers
N(45–60)	135
N(30–45)	45
N(15–30)	5
S(15–30)	2
S(30–45)	4

The data used are from the publicly available collection of observer records provided by the Radio Meteor Observation Bulletin (RMOB). The locations of the observers are spread across the globe. This does not present an issue when considering the data as a whole, since individual observers' variations in data will be insignificant, given a sample size of almost 350. Thus the influence of individual setups is disregarded. Spatial variations may be present: these are considered.

Collection of data from the website was automated using a script. Once obtained as a raw text file, the file was parsed and stored using custom Python objects. 'Observer' objects contain the username, a Python dictionary containing their data, location attributes, and detection setup information for the given observer. The data dictionary was populated with 'Entry' objects, which are a single month of data and contain the date in format YYYY-MM, data source URL, and the data itself. If the same observer reported a different detection setup in a certain month, this was separated into a different object. Some website users used a different username occasionally – these data were combined, provided the detection setup is identical, otherwise placed in a new object.

There were 345 observer objects in total. 213 of these contain both latitude and longitude co-ordinates in decimal degrees. For analysing monthly and annual variation of detection counts, these data were suitably formatted and only required categorising by month or day. For statistical analysis, the data were compiled into a spreadsheet of tuples of detection counts for each hour available, split by latitude class. Longitude classes were not analysed since longitude does not represent a significant effect to be considered. Equally, further splitting the data by longitude as well as latitude would have reduced sample sizes further, making some classes too small to be analysed. Table 1 shows the number of observers by latitude class and period of the day. Note that not all observers with sufficient location data were included, since some do not have enough valid data.

Before being compiled into the spreadsheet, duplicated data were removed, when an observer has entered

---

[1] Exeter Mathematics School, Exeter, Devon, EX4 3PU, United Kingdom

[2] Norman Lockyer Observatory, Sidmouth, Devon, EX10 0NY, United Kingdom

[3] Email: `cpowell@cwp.io`

[4] Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia. Email: `kristina@matf.bg.ac.rs`

IMO bibcode WGN-454-powell-temporal
NASA-ADS bibcode 2017JIMO...45...73P

[a] Accessible at `www.rmob.org`.

Table 2 – Total number of detection counts and removals by latitude class and period of day.

Latitude class (°)	Day counts	Day removals	Night counts	Night removals
N(45–60)	430 685	22 970	312 143	14 346
N(30–45)	191 336	3 736	177 142	2 970
N(15–30)	4 029	0	3 986	0
S(15–30)	4 781	0	3 426	0
S(30–45)	6 691	157	7 236	175

the same set of data twice onto the RMOB website. Data were split into day or night periods by defining night as 12 hours centred at local midnight. Values greater than 1000 were considered too extreme, and were not included. The value at which counts are considered extreme is arbitrary and of little importance. A threshold of 1000 was chosen as it results in the removal of relatively few counts. In total, for latitude classes, there were 637 552 day-time counts after 26 863 were removed, and 503 933 night-time counts after 17 491 were removed. A full breakdown of counts and removals is given in Table 2.

2.2 Research hypotheses

1. Is the effect of year on detection counts significant (e.g. detection counts significantly differ for different years)? Are the detection counts collected during the years 2009–2010 significantly higher than other detection counts?

2. Do time of day and latitude have a significant effect on detection counts? Are the night-time detection counts significantly higher than day-time detection counts? Are there significant differences in detection counts when going from southern latitudes to northern latitudes?

2.3 Statistical analysis

The distribution of the detection counts collected during the period 2000–2016 was analysed with graphical representation (histogram) and with descriptive statistics (mean, median, first and third quartile, coefficients of skewness and kurtosis). Statistical tests for normality were not used. Because of the large sample size, these tests are very sensitive and would detect extremely small departures from a normal distribution.

Fligner-Killen test of homogeneity of variances (Conover et al., 1981) was used to examine if the variability of detection counts collected during the period 2000–2016 is approximately the same. Significance of the effect of year on detection counts was tested by Brunner-Dette-Munk non-parametric one-way ANOVA (Brunner et al., 1997). For examining the effects of period of the day and latitude class on detection counts, Brunner-Dette-Munk non-parametric two-way ANOVA was used. More details about these statistical methods can be found in Rand Wilcox's book (Wilcox, 2012) and complementary R code on his web page (Wilcox, 2016).

Multiple comparisons between detection counts for pairs of years, day-night period of the day, as well as pairs of latitude classes were performed using Brunner-Munzel test (Brunner & Munzel, 2000). The probability of type I error was controlled using Rom's method. Comparisons between two groups were made only if the sample size of the bigger group was at most 100 times greater than the sample size of the smaller group.

P-values < 0.05 were considered statistically significant. Statistical analysis was performed in statistical software R, version 3.4.1 (using packages *e1071*, *lawstat*).

2.4 Monthly & annual variation

In lieu of the statistical analysis, mean ranks were used to analyse variation because the data is asymmetric, so mean is not a good measure of location. Group variances are also not the same, so the data can not be meaningfully compared using median, leaving mean rank as a suitable option. These mean ranks of hourly detection counts for all observers were analysed over monthly and annual timescales, demonstrating the variation of observations in the period 2000–2016.

The hourly detection counts were sorted in increasing order and then ranked. For annual variation of detection counts, the mean rank for each month was calculated by dividing the sum of the ranks of detection counts in that month with total number of monthly counts. Similarly, for monthly variation of detection counts, the mean rank for every day of the month was calculated by dividing the sum of the ranks for that day with the total number of daily counts for that month.

3 Results

3.1 Annual scale variation

The annual variation is shown in Figure 1. The highest mean rank occurs in June. From January to March, there is a decrease in mean rank, followed by a steep increase until June. After this, mean rank steeply decreases until September, with a smaller increase to November, followed by another smaller decrease to December.

3.2 Monthly scale variation

The variation over the course of a month is shown in Figure 2. The variation of mean ranks over the month is small, with no significant increases or decreases except at the beginning of January, the middle of August and the middle of December.

Note that the mean ranks of detection counts for each day of the month are calculated using data from the entire period 2000–2016, so the decrease on the 29th of February occurs due to leap years.

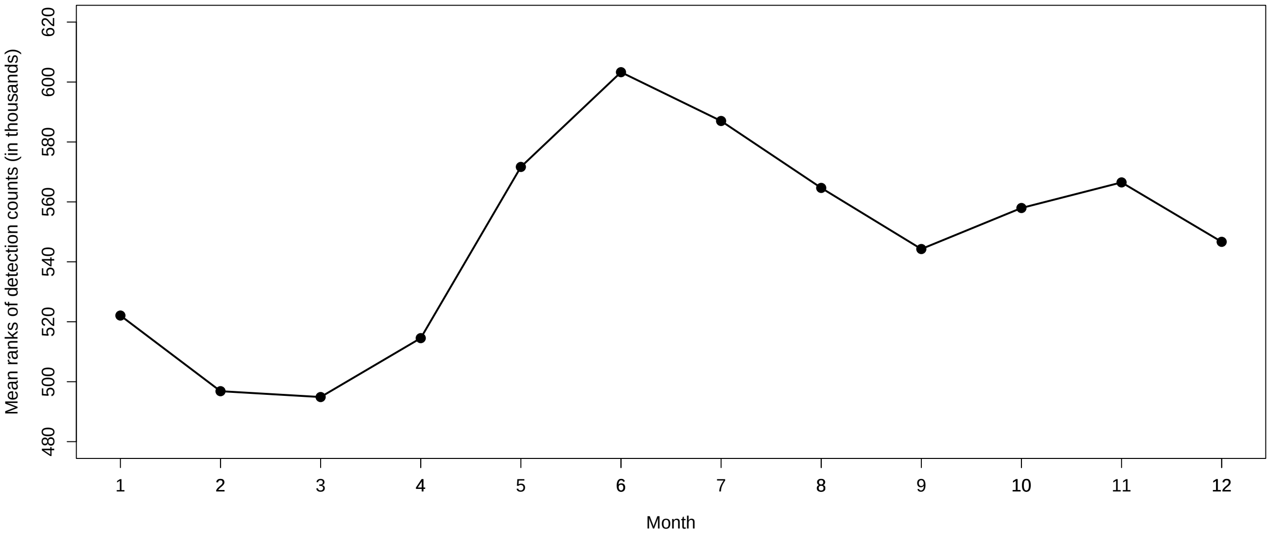

Figure 1 – Variation in mean rank for each month of hourly detection counts collected during the period 2000–2016.

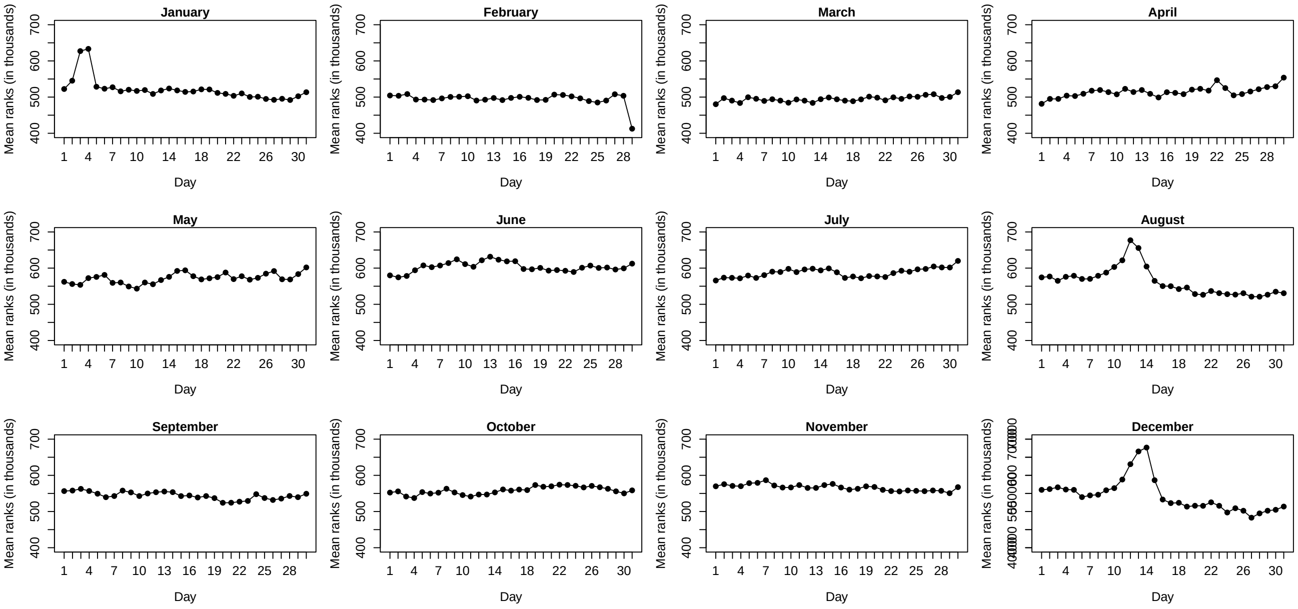

Figure 2 – Variation in mean ranks for each day of each month of hourly detection counts collected during the period 2000–2016.

3.3 Statistical analysis

After removing duplicates and extreme values from the data-set of detection counts, 1 097 101 counts are left. The minimum value of detection counts is 0, and the maximum value is 996. The sample median is equal to 30 and the sample mean to 55.7. The first sample quartile equals 12 and the third is 75. The sample coefficient of skewness is equal to 2.7 and the sample kurtosis, 11.5. The normal distribution has coefficient of skewness equal to 0 and coefficient of kurtosis equal to 3. Values of skewness and kurtosis of detection counts suggest a distribution that is skewed to the right (positively skewed), with higher peak and longer tail than a normal distribution. Detection counts are represented as a histogram in Figure 3. The bins of the histogram are of length 10. In the first bin (0–10 counts) there are 244 364 detections. Starting from the 421–430 bin, frequencies corresponding to the bins are smaller than 302 and can not be seen on the histogram (zero line). In Figure 3, only counts 0–450 are presented.

We will now inspect whether the variability of detection counts during the period 2000–2016 are approximately the same. Using the Fligner-Killeen test of homogeneity of variances ($\chi^2 = 62\,952$, $df = 16$, $p < 0.001$), we can conclude that year variabilities are not the same (in other words, heteroscedasticity of detection counts by year).

As the distribution of the detection counts is very skewed, in testing our research hypotheses, we could not use standard parametric tests. In the case of heteroscedastic data, even median is not a good choice for the measure of comparisons of different groups. Rather,

Table 3 – Summary statistics of detection counts by year.

Year	Number	Min	Max	1.quartile	Median	3.quartile	Mean rank
2000	8 889	1	996	3	10	35	376 040.5
2001	8 341	1	903	10	18	30	421 829.9
2002	8 710	1	949	9	18	32	399 802.5
2003	7 819	1	532	8	16	31	374 920.3
2004	9 924	1	393	6	11	18	280 121.4
2005	5 763	1	464	5	12	25	314 692.0
2006	5 526	1	334	9	17	30	405 231.9
2007	3 978	1	614	9	21	106	523 092.9
2008	1 230	3	395	19	35	57	575 226.5
2009	25 050	1	995	34	94	169	778 523.5
2010	60 198	1	446	26	53	112	696 070.7
2011	71 985	1	668	18	36	86	604 521.2
2012	136 076	1	905	17	38	83	594 963.6
2013	171 149	1	804	11	29	73	538 737.9
2014	191 108	1	778	11	33	83	560 308.3
2015	193 938	0	818	11	28	73	536 771.0
2016	187 417	0	752	10	22	53	478 370.7

in order to compare distributions of detection counts in different groups, we chose a mean rank. All 1 097 101 detection counts are sorted in increasing order and ranked — the smallest count gets rank 1, second smallest rank 2, and so on, with the largest count getting a value of 1 097 101. Then, the mean rank for each group is calculated (for example the mean rank of detection counts in every year from 2000 to 2016). Group mean ranks are compared in statistical tests. For example, for two groups, a higher mean rank means that there are higher detection counts in that group (though not necessarily a greater maximum detection count).

Summary statistics (number, minimum, maximum, first and third quartile, median and mean rank) of detection counts by year are presented in Table 3.

Mean ranks of detection counts by year are presented in Figure 4. It can be seen that detection counts vary by year. The highest detection counts occurred between 2009 and 2010.

The significance of the effect of year on detection counts is confirmed by Brunner-Dette-Munk nonparametric one-way ANOVA ($F = 2\,158.974$, $df_1 = 6.03$, $df_2 = 12\,429.09$, $p < 0.001$). We will now test the hypothesis that detection counts in 2009 are higher than detection counts in 2010, as well as the hypothesis that detection counts in 2010 are higher than counts in other years. Formally, we first test the existence of difference in detection counts for 2009 and 2010, as the hypothesis is set before seeing the data. The directional hypothesis that detection counts in 2009 are higher than detection counts in 2010 is tested afterwards. Although this can be considered biased, a directional hypothesis is of greater practical significance. Brunner-Munzel test was used for multiple comparisons between two

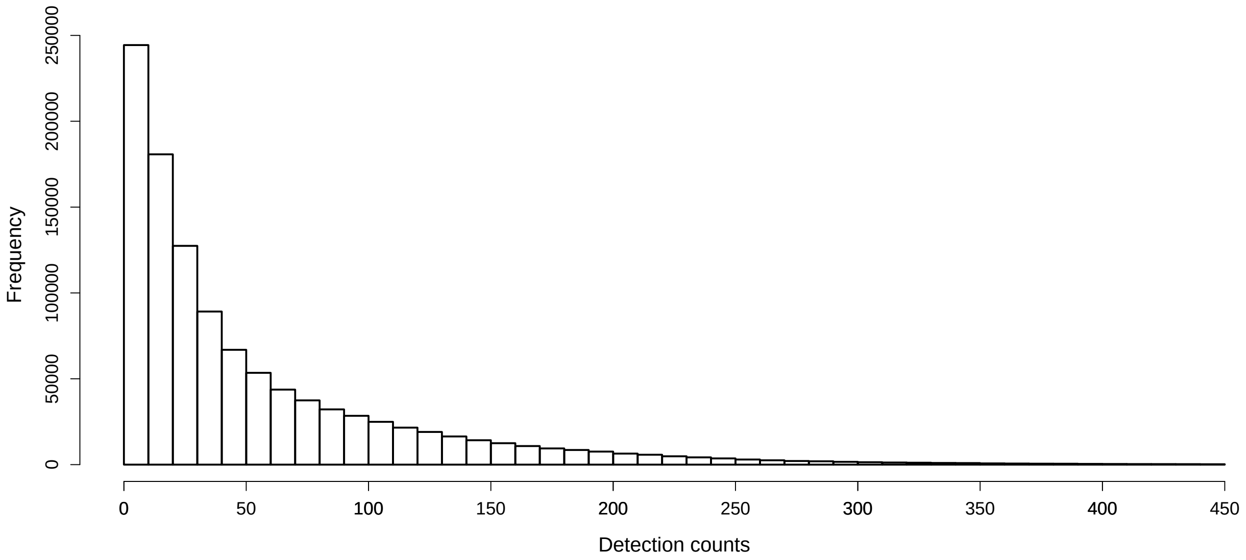

Figure 3 – Histogram of detection counts.

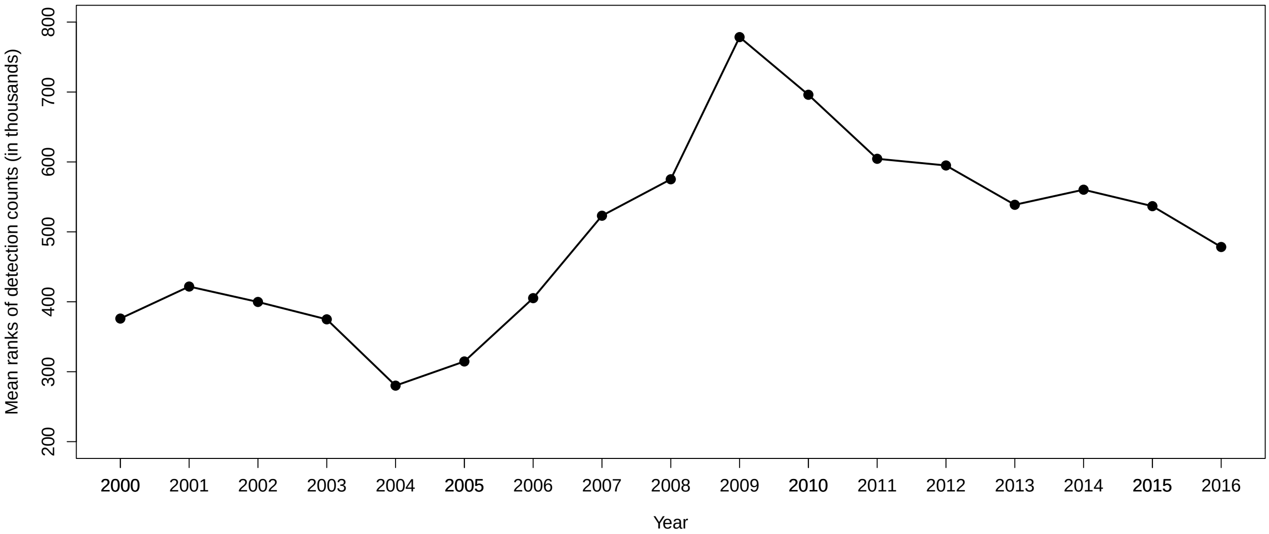

Figure 4 – Plot of mean ranks of detection counts collected during the period 2000–2016.

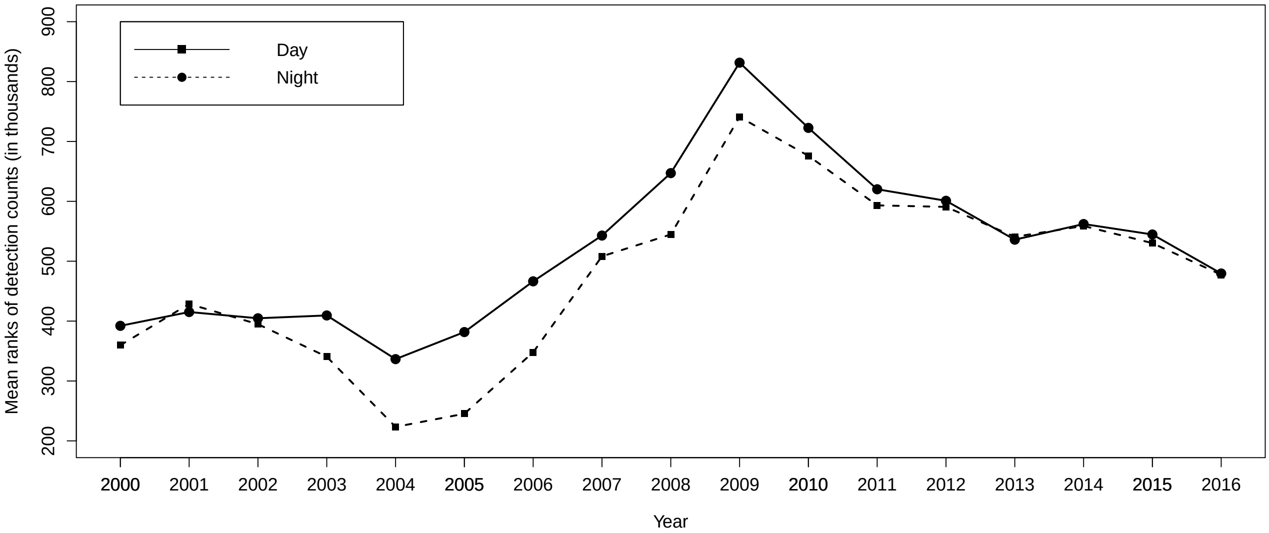

Figure 5 – Plot of mean ranks of day-time and night-time detection counts collected during the period 2000–2016.

groups of year detection counts. It was confirmed (in all cases $p < 0.001$) that detection counts in 2009–2010 are higher from other detection counts, and that detection counts for 2009 are the highest.

We will now test the hypothesis about the significance of the effects of period of the day and latitude class on detection counts. As the effect of year on detection counts is significant, we will perform analyses for each year separately, including a separate ranking of the data by year. The number and mean rank of detection counts by year, period of the day, and latitude class are given in Table 4. There is no year where all latitude classes are considered.

In the years 2005–2016 there were at least two latitude classes and the analyses of the effects of the period of the day and latitude class on detection counts could be performed. In 2004, although the N(45–60) class is available, the sample size is more than 100 times smaller than the N(30–45) class. For testing the hypothesis, we used the Brunner-Dette-Munk non-parametric two-way ANOVA. For all the years in that range, the interaction effect of period of the day and latitude class on detection counts is significant. As this interaction effect is not part of the research hypotheses and is difficult to interpret, we will not analyse it in more detail. Also, the effect of period of the day on detection counts is significant in years 2005–2010 and 2012–2015. In 2011 ($p = 0.367$) and 2016 ($p = 0.172$) no difference between day-time and night-time detection counts was found. Effect of latitude class on detection counts in years 2005–2016 is significant.

We will first compare day-time and night-time detection counts, and then detection counts in latitude classes. Multiple comparisons between a selection of two classes were performed using the Brunner-Munzel test. For the years 2012–2015 and for some pairs of the

Table 4 – Number N and mean rank $\overline{R}$ of detection counts by year, latitude class and the period of the day.

	Day-time				Latitude									
	Day		Night		S(30–45)		S(15–30)		N(15–30)		N(30–45)		N(45–60)	
Year	N	$\overline{R}$	N	$\overline{R}$	N	$\overline{R}$	N	$\overline{R}$	N	$\overline{R}$	N	$\overline{R}$	N	$\overline{R}$
2000	4 114	4 396.6	4 475	4 492.7	—	—	—	—	—	—	8 889	4 445.0	—	—
2001	4 112	4 323.7	4 229	4 022.6	—	—	—	—	—	—	8 341	4 171.0	—	—
2002	4 346	4 313.7	4 364	4 397.2	—	—	—	—	—	—	8 710	4 355.5	—	—
2003	3 915	3 560.7	3 904	4 260.3	—	—	—	—	—	—	7 819	3 910.0	—	—
2004	4 947	4 054.7	4 977	5 864.8	—	—	—	—	—	—	9 838	4 920.6	86	9 754.8
2005	2 832	2 333.4	2 931	3 412.0	—	—	—	—	—	—	5 612	2 814.9	151	5 377.1
2006	2 853	2 290.9	2 673	3 267.9	—	—	—	—	—	—	5 065	2 540.0	461	5 219.2
2007	2 268	1 888.3	1 710	2 123.8	—	—	—	—	—	—	2 475	1 269.5	1 503	3 175.1
2008	863	565.5	367	733.1	—	—	—	—	—	—	567	810.3	663	448.9
2009	14 658	11 287.7	10 392	14 271.5	—	—	—	—	—	—	3 217	3 422.2	21 833	13 866.8
2010	34 316	28 669.4	25 882	31 995.6	79	668.2	—	—	—	—	15 375	19 994.3	44 744	33 623.8
2011	41 921	35 154.6	30 064	37 162.1	1 041	3 717.6	—	—	24	31 224.2	23 103	31 688.1	47 817	38 778.0
2012	79 617	67 428.6	56 459	68 898.5	—	—	3 609	11 010.9	—	—	34 148	64 680.0	98 319	71 298.3
2013	97 633	85 896.8	73 516	85 147.7	—	—	4 514	13 291.8	4 631	72 606.7	52 246	75 750.8	109 758	93 771.4
2014	106 062	95 247.7	85 046	95 937.1	415	20 747.7	—	—	1 147	113 100.0	71 056	101 764.4	118 490	91 922.7
2015	106 107	95 817.0	87 831	98 361.9	6 123	105 943.3	84	60 377.1	—	—	56 192	92 753.7	131 539	98 376.1
2016	99 795	93 530.3	87 622	93 912.6	5 937	82 949.1	—	—	2 213	84 153.8	49 119	80 725.9	130 148	99 262.3

groups, Brunner-Munzel statistics could not be calculated. In these cases, the Wilcoxon sum rank test was used instead.

Mean ranks of day-time and night-time detection counts by year are represented in Figure 5. In most years, night-time detection counts are higher than day-time detection counts.

Results of the multiple comparisons between day-time and night-time detection counts are given in Table 5. By the formal statistical testing, it is confirmed that for 12 out of 17 years, night-time detection counts are higher than day-time detection counts.

We should note that, although the two-way ANOVA did not find any significant differences between day-time and night-time detection counts in 2011, further analyses (Brunner-Munzel test) showed that a difference probably exists ($p < 0.001$).

Mean ranks of detection counts in latitude classes by year are presented in Figure 6. The detection counts vary greatly in the same latitude class by year. In most years, detection counts in the N(45–60) class are higher than detection counts in the N(30–45) class.

Results of the formal testing of the differences between detection counts in latitude classes is given in Table 6. In the third column of the table are listed classes excluded from the multiple comparisons because of a sample size that is too small. The detection counts in the N(45–60) class are higher than detection counts in the N(30–45) class in 10 out of 12 years where both classes have large enough sample sizes.

4 Discussion

4.1 Effect of year on detection counts

The apparent maximum in detection counts between 2009–2010 is significant. This period is the same as the period of solar minimum (Figure 7). This correlation between solar minima and radio meteor detection counts maxima is noted in other articles (Lindblad, 1968).

That the solar cycle has an impact on meteor detection rates is not unexpected; the solar cycle heavily influences solar wind and electron line density in the upper atmosphere, and this has been known for some time (Wright, 1962). These changes in the ionosphere can have a large influence on detection rates, especially for radio meteor detection. It is necessary to ask whether the detection count maximum is a result of reduced noise, or an enhancement of radio signal intensities. No analysis of this is made.

Analysis of fit between an idealised diurnal shift curve and a given observer's data (Powell, 2017) suggests that the background detection rate increases between 2005 and 2011, but the intensity of diurnal shift does not, supporting the result that there is an increase in detection counts between 2009 and 2010. The density of debris surrounding Earth is likely not the cause of the detection count maximum, since this would also increase the intensity of diurnal shift. Rather, the noted maximum in detection counts must be due to better detecting conditions.

4.2 Effect of latitude on detection counts

Our results indicate (but do not fully confirm) that greater hourly detection counts are seen at greater latitudes. Whilst this appears to contradict Singer et al.

Table 5 – Relationship between day-time and night-time detection counts by year.

Relationship between day and night counts	Year
day = night	2000, 2002, 2016
day > night	2001, 2013
day < night	2003–2012, 2014–2015

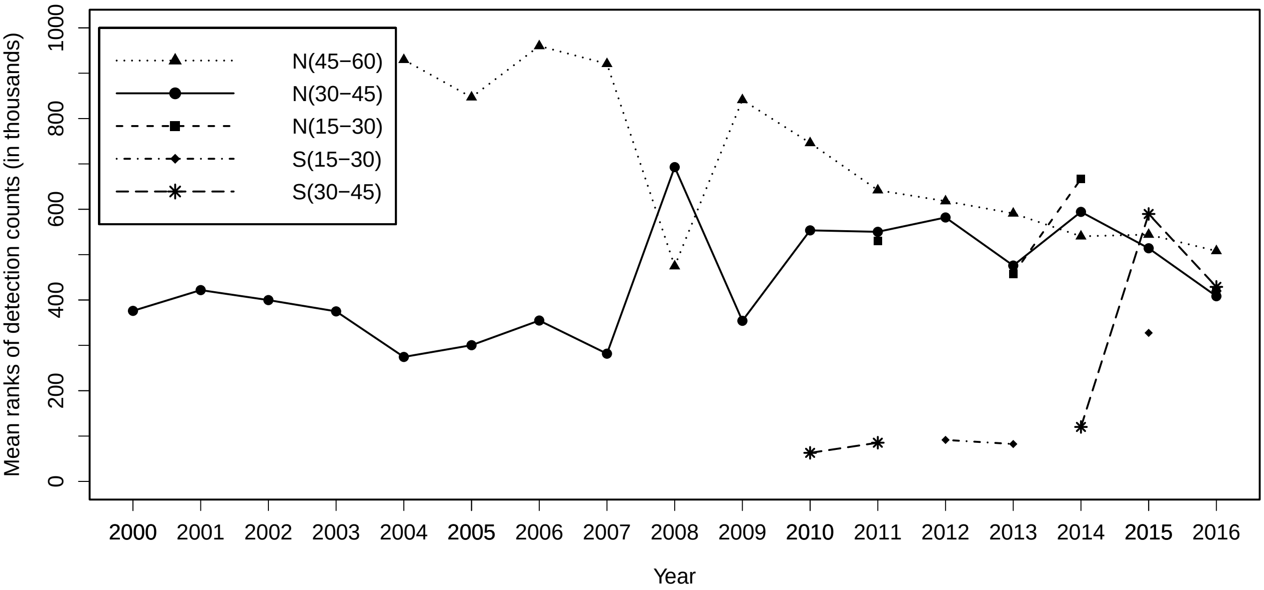

Figure 6 – Plot of mean ranks of detection counts in latitude classes collected during the period 2000–2016.

(2005), their research noted a relationship between diurnal rates and latitude, not overall detection rates as in our research. It is not clear why detection counts would be affected by latitude, nor why both latitude and period of the day interact to cause an effect.

A statistically significant difference in detection rates is found with class N(45–60) observing greater hourly detection counts than N(30–45) in 10 of 12 years. However, overall the relationship between latitude and detection counts is not clear.

4.3 Day-time and night-time rates

The fact that there is a statistically significant increase in detection rates during night-time could be due to many effects. A likely explanation is due to the change in ionospheric structure at night. With the absence of solar excitation, the ionisation of the D and E layers dramatically decreases, whilst the F layer remains well ionised, resulting in more free electrons, enabling radio signals to travel further — this was first reported in 1938 and is well studied (Booker & Wells, 1938). This effectively increases the area over which meteors can be detected, resulting in slightly higher detection rates. The effect is not large, since the increase in detection capability in the area of atmosphere where meteor burn-ups occur is little — it is largely an increase in range.

Theoretically, the peak hour of diurnal shift occurs at 6am, so any influence will be uniform between day and night (with the method of defining day or night as defined), and thus this phenomenon can be disregarded.

Table 6 – Relationship between detection counts in latitude classes by year.

Year	Relationship between latitude counts	Excluded latitude class
2005–2007, 2009	N(45–60)>N(30–45)	—
2008	N(45–60)<N(30–45)	—
2010	N(45–60)>N(30–45)	S(30–45)
2011	N(45–60)>N(30–45)>S(30–45)	N(15–30)
2012	N(45–60)>N(30–45)>S(15–30)	—
2013	N(45–60)>N(30–45)>N(15–30)>S(15–30)	—
2014	N(15–30)>N(30–45)>N(45–60)	S(30–45)
2015	S(30–45)>N(45–60)>N(30–45)	S(15–30)
2016	N(45–60)>N(15–30)>N(30–45)=S(30–45)	—

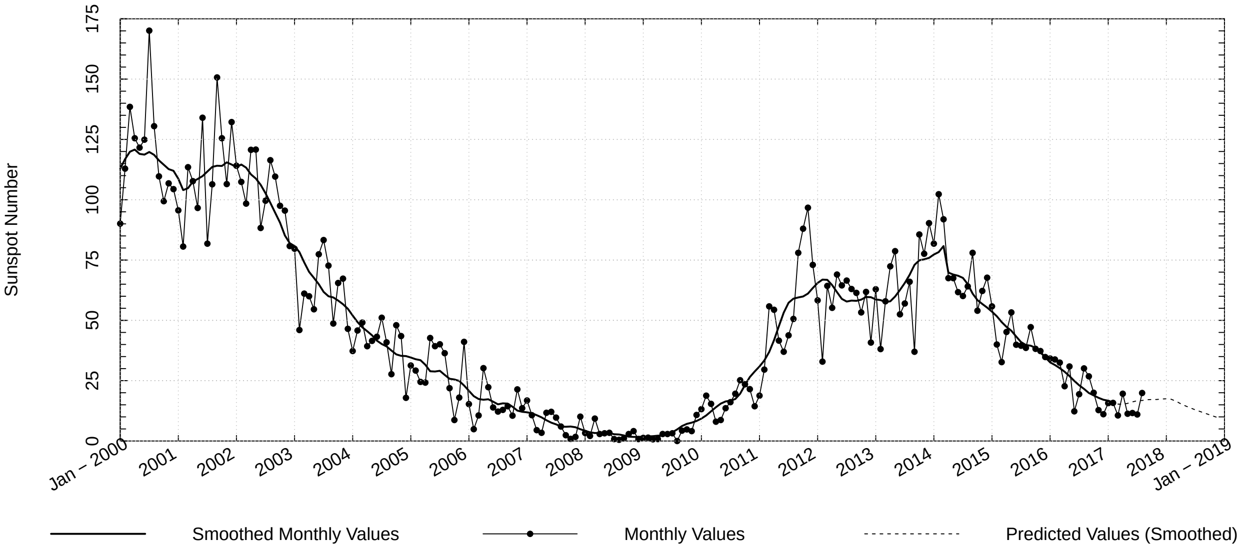

Figure 7 – Solar cycle sunspot number over time, observed data through 2017 August (Data provided by NOAA/SWPC (`http://www.swpc.noaa.gov`)).

There is a potential inaccuracy in the way day-time and night-time is defined for this analysis. Choosing night as a 12 hour period centred on local midnight allows analysis of the data whilst avoiding a large degree of complexity in calculating actual day and night for the observer. However, this simplification means that some items of data may be considered part of the day, but where recorded during the night. Overall this effect should be minimal, since the definition of day as 12 hours centred at midnight used can be viewed as an 'average' day across an entire year.

4.4 Annual scale variation

The increase in the middle of the year may be due to an increased number of meteor showers, or another phenomenon. This increase is likely due to an event or mechanism occurring during summer in the Northern Hemisphere, since most observers in the sample are in the Northern Hemisphere. The summer increase is in agreement with Singer et al. (2005).

The mid-year increase is likely not due to Earth's position relative to other bodies, which may sweep up meteors. The observed variation is an apparently annual occurrence, but Earth's position relative to other bodies is not periodic over the same period.

4.5 Monthly scale variation

It is unsurprising that there is no overall trend over the course of any month. Any variation on this scale could potentially (though unlikely to) be caused by the moon, though it is unlikely that it would have a significant impact, and this is seen in the results. The only clear increases in any month are the major meteor showers, namely the Perseids in August, Geminids in December, and Quadrantids in January.

4.6 Hemispheric effects

Specific northern and southern sources of meteors exist. Thus the temporal variations of hourly detection counts may be different between each hemisphere. However, variation over periods beyond a year are unlikely to be affected, since any difference between the hemispheres would counteract one another. Effects over shorter periods, such as sub-annually, may not counteract. Differences in sub-annual and sub-monthly variations should be considered in more scrutiny by hemisphere. Only 9 observers from the available data used for this analysis are in the Southern hemisphere, making any conclusions difficult to obtain. Therefore these effects have not been considered and are an important analysis to make in the future.

5 Conclusion

1. There is no clear variation in hourly detection counts over a month other than due to major meteor showers.
2. An increase in detection counts is observed during the summer months, with no clear explanation.
3. A statistically significant increase in hourly detection counts is present between 2009 and 2010.
4. The noted increase in meteor detection counts between 2009 and 2010 appears to correlate with a solar minimum, supporting hypotheses from Lindblad (1968) and Bumba (1949).
5. The effect of period of the day and latitude on detection counts is statistically significant.
6. For 12 out of 17 years between 2000 and 2016, night-time detection counts are greater than day-time detection counts, potentially due to changes in ionospheric structure between day and night.

7. In 10 out of 12 years tested between 2000 and 2016, observers in latitudes 45°–60° observe greater detection counts than observers in latitudes 30°–45°.

Acknowledgements

Permission for the use of data is kindly provided by the RMOB organisation. This work has in part been supported by the Norman Lockyer Observatory[b] and Exeter Mathematics School[c]. We are grateful to Michael Andrejczuk and Malcolm Simpson for their suggestions and advice.

References

Booker H. G. and Wells H. W. (1938). "Scattering of radio waves by the F-region of the ionosphere". *Journal of Geophysical Research*, **43:3**, 249–256.

Brunner E., Dette H., and Munk A. (1997). "Box-type approximations in non-parametric factorial designs". *Journal of the American Statistical Association*, **92**, 1494–1502.

Brunner E. and Munzel U. (2000). "The nonparametric Behrens-Fisher problem: asymptotic theory and a small-sample approximation". *Biometrical Journal*, **42**, 17–25.

Bumba V. (1949). "Influence de l'activité solaire sur le nombre des observations de météores, de traînées météoriques et de chutes météoriques". *Bulletin of the Astronomical Institutes of Czechoslovakia*, **1**, 93–95.

Conover W. J., Johnson M. E., and Johnson M. M. (1981). "A comparative study of tests for homogeneity of variances, with applications to the outer continental shelf bidding data". *Technometrics*, **23**, 351–361.

Lindblad B. A. (1968). "Long-term variations in meteor radar rates, meteor heights and radar-echo amplitudes". In Kresak L. and Millman P. M., editors, *Physics and Dynamics of Meteors*, volume 33 of *IAU Symposium.* pages 50–62.

Powell C. (2017). "Modelling and analysis of diurnal variation in meteor flux". *WGN, Journal of the IMO*, **45:2**, 32–37.

Singer W., von Zahn U., Batista P. P., Fuller B., and Latteck R. (2005). "Diurnal and annual variations of meteor rates at latitudes between 69°N and 35°S". In Warmbein B., editor, *17th ESA Symposium on European Rocket and Balloon Programmes and Related Research*, volume 590 of *ESA Special Publication.* pages 151–156.

Wilcox R. (2012). *Introduction to Robust Estimation and Hypothesis Testing, First Edition.* Elsevier.

Wilcox R. (2016). "R code". `http://dornsife.usc.edu/assets/sites/239/docs/Rallfun-v33.txt` .

Wright J. W. (1962). "Dependence of the ionospheric F region on the solar cycle [Letter to the editor]". *Nature*, **4827**, 461.

Handling Editor: Javor Kac
This paper has been typeset from a LaTeX file prepared by the authors.

---

[b] `http://www.normanlockyer.com`

[c] `https://www.exetermathematicsschool.ac.uk`