FIRST STEPS TOWARDS *K* INDICES FROM SOUTH ATLANTIC OBSERVATORIES: PORT STANLEY OBSERVATORY

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ABSTRACT

To enhance the quality and near real time production of K-based planetary magnetic activity indices, such as am, and longitude-sector indices, aλ, there is a requirement for local three-hourly K index values from the South Atlantic observatory at Port Stanley. We describe the computer algorithm used to estimate the solar regular variation, S_R, and techniques used to establish the parameters required to derive the K indices. We analyse the results by comparing the distributions of K values with observatories at similar geomagnetic latitude and thus with likely similar levels of geomagnetic activity. We also look for biases by comparing the indices directly to those from nearby observatories. Both sets of results show a good overall agreement. However adjustment of input parameters will be necessary if improved agreement with the indices from the other observatories is required.

Keywords: Geomagnetism, *K* indices, Computer derivation

1   INTRODUCTION

Planetary geomagnetic activity indices are much used in solar terrestrial studies and space weather applications. They are also used to aid data selection in the development of global geomagnetic models. The production of these indices relies entirely on geomagnetic observatories around the world. The production of *K* indices from various individual observatories is required to compute *K*-derived planetary indices. One of these is the *am* index, which was designed to cover all local time (LT) zones and relies on a large network of observatories that are subdivided into nine groups. These groups are also used to represent sectors for the production of the longitude sector index, *aλ*. Further information is given in Menvielle *et al.* (2011) and Menvielle & Paris (2001). Port Stanley (PST) is a remote observatory in the south Atlantic which began operations in 1994. Although it is not part of the definitive network of observatories for these indices, PST is a backup to the observatories in the G9 longitude sector for the production of real time quick-look versions. It has therefore become necessary to establish a method to derive *K* indices for PST, and make these values available for direct use in the derivation of *am* and *aλ* as required.

The *K* index, introduced by Bartels, Heck, and Johnston (1939), is an index designed to quantify the level of disturbance caused by the influence of the solar wind at a single location using magnetic observatory measurements. It is produced for eight three-hour segments in a UT day. The *K* index for each three-hour interval is derived from the larger of the two ranges in the horizontal components *D* (declination) and *H* (horizontal intensity) after the subtraction of the regular daily variation S_R. This range, measured in nT, is denoted by a single digit code from 0 to 9 according to a quasi-logarithmic scale where *K*=0 indicates completely quiet conditions and *K*=9 indicates highly disturbed conditions. It is worth noting that the numbers of the *K* scale are simply a code and the scale could well have been represented by letters rather than numbers.

Traditionally, *K* indices were determined by hand. Skilled observers would examine daily magnetograms and, through experience of S_R variations throughout a year, would judge the S_R variation for the day and scale the *K* values appropriately. Hand scaling of *K* indices is inherently subjective as each observer will interpret events in slightly different ways. For example, Riddick and Stuart (1984) found a level of agreement between two observers hand scaling *K* indices for the three UK observatories to be at a level of between 82-91%. With the

advent of digital data, automatic computed K scaling was introduced to eliminate the variability between hand scalers, to save observers time and to allow real-time access to these data products. In 1991 IAGA approved four computer-based algorithms alongside the hand scaled method of K generation. These algorithms, (summarised in Menvielle et al., 1995) form the basis of all computer derived K indices.

The challenge in scaling K is in determining the solar regular diurnal variation S_R. On quiet days, with little geomagnetic activity, it is referred to as the S_q variation and might be considered straightforward to determine. It has long since been established that there is a seasonal and solar cycle variation in S_q. This on its own would be simple to account for; however, it has also been established by researchers that there is a day-to-day variability in S_q that is much less predictable (see for example Brown & Williams, 1969; Butcher & Brown, 1981). As well as this there is also the occurrence of abnormally quiet days, described by Brown and Williams (1969) and discussed in Butcher et al. (1993) among others. These are days where the phase and amplitude of the diurnal variation are significantly different from that expected.

For computer derivation of S_R this variability needs to be accounted for by deriving the curve on a day-to-day basis, rather than using a fixed S_q curve. The difficulty then is for more unsettled days, where using the data to establish the true S_R is not straightforward. Indeed it is here where most disagreement occurs between different hand scalers as they are required to estimate S_R based on knowledge of what a similar S_q day would look like. Similar subjectivity is likely in the development of a computer algorithm. However, once established, true homogeneity of the results will be achieved, unlike with hand-scaling. For more disturbed days automated K derivation becomes much easier. According to Mayaud (1980) when geomagnetic disturbance is too great to identify S_R, no assumed S_R should be applied. Therefore, in this case the range becomes a simple difference between the maximum and minimum values in each three-hour period (max-min method).

In 1991 the British Geological Survey (BGS) adopted a method for computing K indices for the three UK observatories (Clark, 1992) based on Nowożyński et al. (1991), one of the four IAGA-sanctioned methods. This paper describes recent attempts to begin producing computer generated K indices for PST. It is hoped that once established we can apply the same technique to derive K indices at other overseas observatories operated by BGS including the existing South Atlantic observatory on Ascension Island (ASC) and a new observatory currently being installed on South Georgia.

2   DETERMINING S_q AT PORT STANLEY

It has been established that S_q is too variable to be used to define a fixed S_R curve for direct computation of K indices. However, it was considered relevant to estimate S_q at PST to see if it could be used in any way to help with the development of the algorithm and derivation of the parameters required. In doing this, an S_q model for the observatory was produced. First, the mean daily variation curves were derived from all available PST X (north), Y (east), and Z (vertical) hourly mean data over one solar cycle (1998 to 2009). Data from the five international quietest days in each month were individually de-trended and mean-subtracted then grouped by Lloyd's seasons: D (Jan, Feb, Nov, Dec), E (Mar, Apr, Sep, Oct), and J (May, Jun, Jul, Aug). The X, Y, and Z variations were then converted to D and H variations using the mean values of X, Y, and Z from all selected data in the appropriate Lloyd's season. A Fourier model was then derived for each component and season with 24, 12, 8, and 6 hour coefficients.

The modelled D and H S_q curves for each component and season were plotted along with the quiet day hourly mean data that were used in the derivation. An example of this is shown in Figure 1. The variability of S_q, compared with the average behaviour exhibited by the model, is clear, and although this model could be useful in other applications its usefulness in the selection of S_R algorithm parameters was deemed to be minimal.
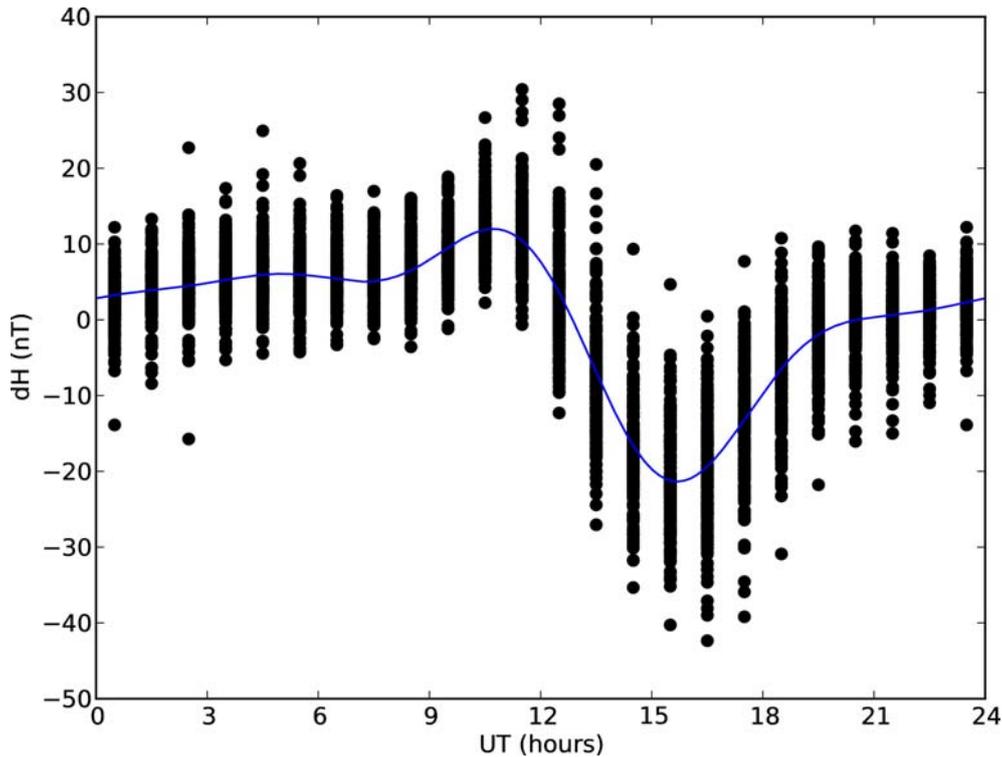
Figure 1. An example of the modelled S_q curve produced for PST. This shows all the hourly mean values for PST *H* for the five international quiet days in equinoctial months (Mar, Apr, Sep, Oct) from 1998 to 2009 (black dots) and the Fourier fit to the data (blue solid line).

3   METHOD

3.1   Determining the *K* scale for PST

Before we began to derive *K* indices, it was first necessary to determine the lower limits of each class in the *K* scale for PST. When devising the *K* index, it was Bartels's intention that a given value of *K* would have the same significance at all observatories regardless of latitude. The *K*=9 lower limit for a particular observatory is determined by the International Service for Geomagnetic Indices (ISGI) by the use of grids that attempt to implement Bartels's principle (Menvielle & Berthelier, 1991). The other limits are set proportionally to the scale of Niemegk Observatory, and originally defined by Bartels et al. (1939). This follows a quasi-logarithmic scale to resolve both lower level activity as well as higher activity levels. For PST the lower limits of the local *K* scale are as given in Table 1.

Table 1. Lower limits (nT) of the *K* scale for Port Stanley Observatory

K	0	1	2	3	4	5	6	7	8	9
Lower limit (nT)	0	3	7	13	26	46	79	131	216	328

3.2   BGS *K* scaling methodology

The algorithm used to produce *K* indices from PST is the same method currently used by BGS to produce *K* indices for the three UK observatories. This method, based on the adaptive smoothing method proposed by Nowożyński et al. (1991), is described in detail in Clark (1992).

To determine S_R we use the following expression (Eq.1):

$$\sum_{i=1}^{1440} \lambda_i^2 (y_i - x_i)^2 + \sum_{i=2}^{1439} (y_{i+1} - 2y_i + y_{i-1})^2$$

(1)

where x_i are the 1440 minute mean values for D or H and y_i are the 1440 values of the S_R curve. By minimising this expression we can determine the S_R curve, y_i. The first term represents the fit of y to x. The second term represents the curvature of the estimated S_R variation. Altering the value of λ^2 changes the relative importance of each term. The S_R curve can be made to fit the data more closely by increasing the size of λ^2. Conversely, reducing λ^2 will lessen the fit of S_R to the data and make it smoother. If $\lambda^2=0$, S_R is an undetermined straight line.

The implementation of the algorithm for PST is as determined by Clark (1992). First a preliminary S_R curve is determined from a least-squares fit of the data using an initial value of λ^2. If, in any three-hour period, the preliminary K is greater than a threshold, λ^2 is decreased during a second run (λ_u^2) in order that the estimated S_R will not follow large irregular disturbances. Also, if the preliminary K exceeds a second threshold, the S_R curve is ignored, and only the range (max-min method) is used to compute the final K. Clark observed that when comparing computed K to hand-scaled K the algorithm required further adjustment to reduce bias in season and UT. Hence weighting factors for these were also introduced for the UK observatories.

To compute K values for PST there are a number of parameters that must be determined. We need to find values for λ^2 and λ_u^2 and set a threshold to change between them. We must also determine a second threshold to enable automatic switching to the max-min scaling and determine weightings for both season and UT time periods. For the UK observatories, an 80% agreement between the computed and hand scaled K was the goal, matching the agreement commonly seen between two independent hand scalers. Parameters and thresholds were adjusted until this level of agreement was achieved. For PST, using the λ^2 and λ_u^2 values and thresholds established for Hartland Observatory (Clark, 1992) as an initial guide and after several iterations of adjusting using a combination of experience and trial and error, a preliminary set of parameters were established. Further explanation of this process is given in the following section and attempts to verify the selected parameters are described in Section 5.

4   DETERMINING λ^2: ADAPTIVE FITTING OF S_R

To establish the parameters required by the algorithm, we began by producing K indices for a variety of λ^2 with no seasonal or UT weighting applied. We produced a series of quiet-day magnetograms for D and H showing the observatory data and the S_R curve computed. The modelled S_q curve for that season, as described in Section 2, was also included for reference. An example of this is shown in Figure 2, and as per the conclusions earlier it was apparent that there was too much day-to-day variation for the model to be useful for parameter selection. We used visual inspection of these magnetograms and as systematic an approach as possible to vary the λ^2 and λ_u^2 values to select the parameters that gave the best fit of S_R to the observatory data. We first examined the equinoctial months as there would be no seasonal weighting applied to these months. Through an iterative process we examined the effect of various λ^2 and selected first a value for λ^2 and then, after further examination, a value for λ_u^2. The threshold for λ_u^2 was set at $K > 0$ following Clark (1992). Thresholds of both $K>4$ and $K>5$ were investigated for switching to the max-min method.

During this process we aimed to follow the original principles set out for the derivation of the K index. The S_R curve should follow the regular solar variation and not follow any irregular variation of the data. Therefore the algorithm is required to adapt depending on activity levels. Changing the value of λ^2 ensures a smoother fit when required, and the program does not fit a curve at all when it gets above a certain activity level. Whilst the process of visual examination is subjective, like hand scaling, data were examined by two observers to try and mitigate the effect of this subjectivity.

Once we had established the first set of parameters, we examined data for summer and winter months to establish seasonal weighting. Then we examined the computed S_R and corresponding K during daytime hours and judged the appropriate weights for each 3-hour period. Table 2 shows the preliminary optimum parameters selected for further analysis. Figure 3 shows two examples of the magnetograms examined. They show the observatory D and H data and the S_R curve applied by the algorithm. The top magnetogram shows a quiet day with a well-defined S_q curve. Note how this curve doesn't follow the data during irregular variation between 18-21UT. The bottom magnetogram shows a disturbed day. Note how the data are not fitted with an S_R curve at the start and end of the day where activity levels are too great.

Table 2. Values of the preliminary parameters selected for the generation of PST K values

Parameter	Port Stanley
λ^2	0.5×10^{-6}
λ_u^2	0.1×10^{-6}
λ_u^2 threshold	1
Max-Min threshold	4
weight 09-12UT	2.0
weight 12-15UT	5.0
weight 15-18UT	3.0
weight summer	0.8
weight winter	1.2
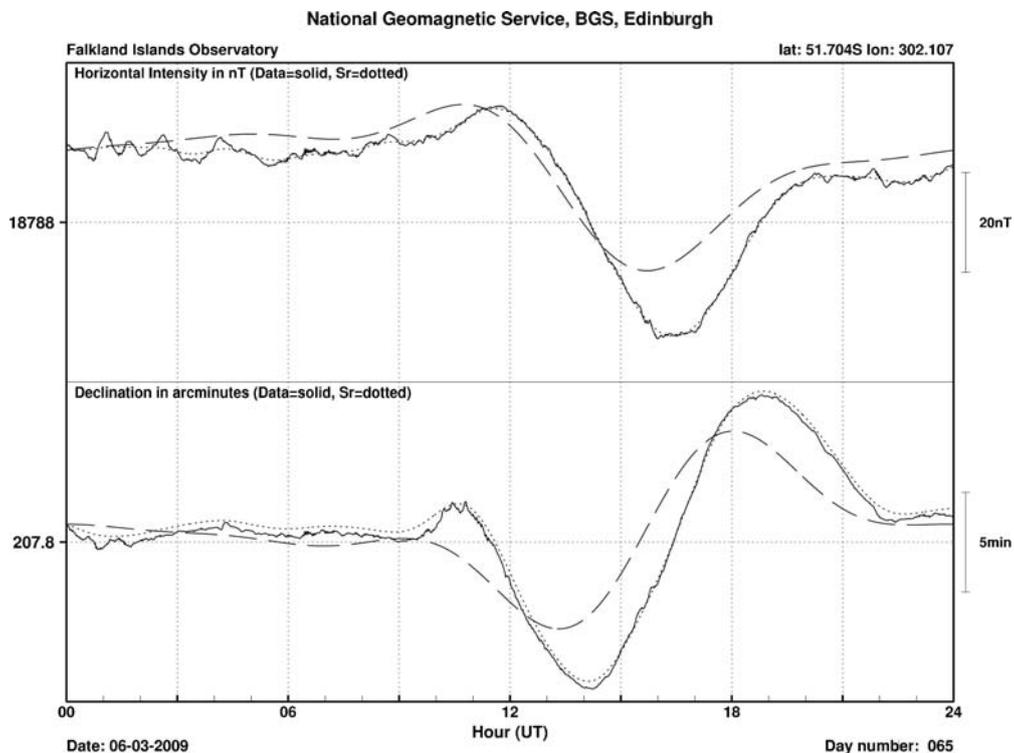
Figure 2. An example quiet-time magnetogram for PST showing the observatory one-minute data for D and H (solid line), the S_R curve produced by the algorithm (dotted line), and the modelled S_q curve for that season (dashed line).
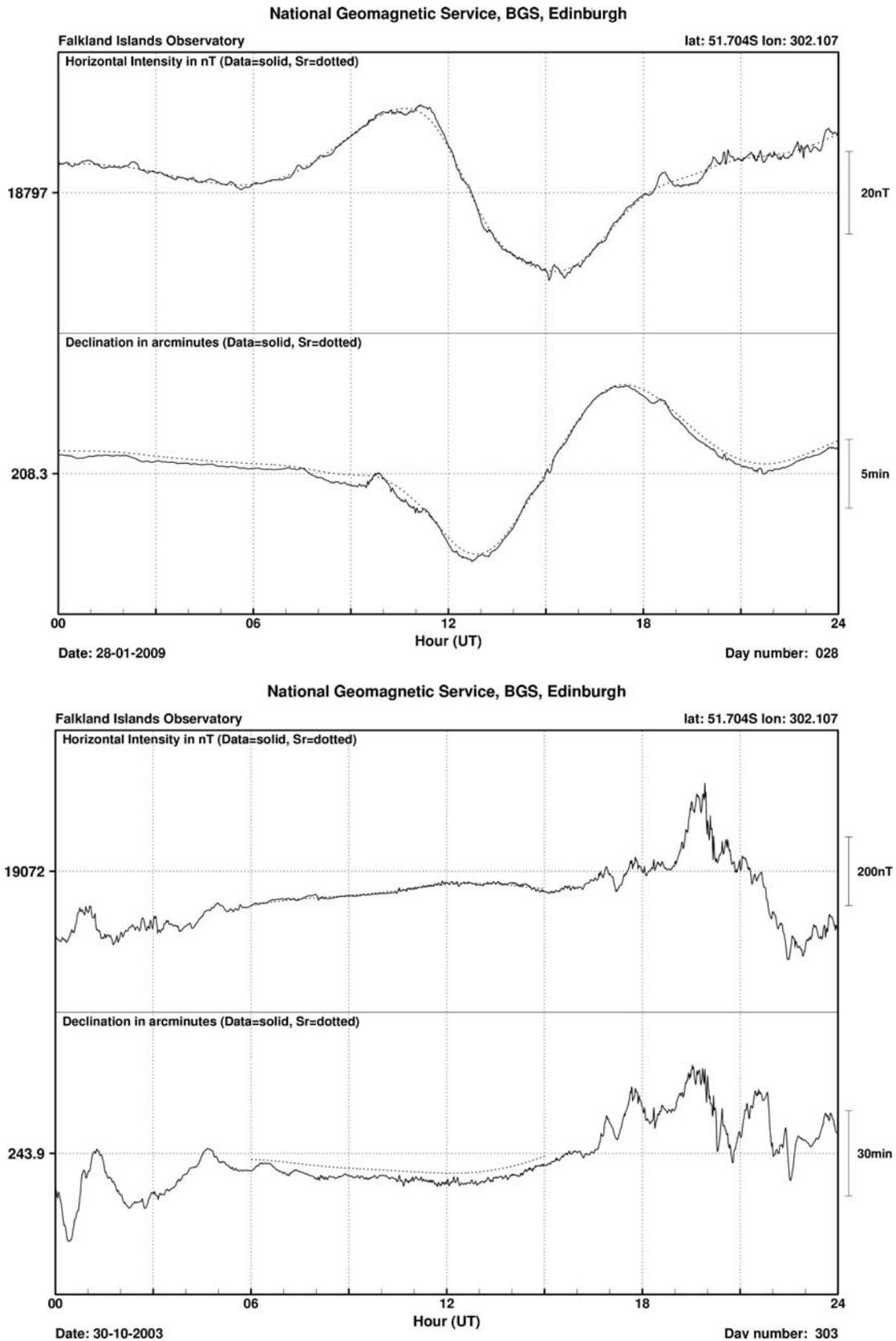
Figure 3. Example magnetograms showing the S$_R$ curve fitting to *D* and *H* one-minute values. A geomagnetically quiet day (top) and disturbed day (bottom) are shown.

5 ANALYSIS OF *K* INDICES

Once preliminary parameters to derive PST *K* indices were selected, the results were analysed to check that the values produced by the algorithm were appropriate. In most cases where new automatic *K* derivation techniques are developed, this type of analysis is done by comparing the computer derived *K* to hand scaled *K*. This is a requirement to maintain the homogeneity of the data set in question and not necessary in this case as there are no previously hand scaled *K* indices for PST. When developing the automatic *K* indices for the UK observatories, Clark (1992) adjusted the algorithm parameters to obtain the best match to the published hand scaled values. These may not have been the most appropriate parameters possible for these observatories and resulted in retaining any bias from the hand scalers of the time in the computer derived values. Whilst we are free from this problem in this case, it does make it more difficult to find a "valid" method of checking the algorithm being developed for PST.

We opted to compare the PST results to other observatories with readily available *K* indices at either similar geomagnetic latitude and/or located in a similar local time-zone. Table 3 lists the observatories used in this analysis and includes quasi-dipole latitude[1], time-zone, and lower *K*=9 limits for each. It is important to note that no consideration has been given to the method used by each of these observatories for processing the data and deriving the indices, nor has the data quality been assessed by the authors. As these are observatories judged to have met the INTERMAGNET standards of operation, processing, and quality, the published *K* indices from each can be considered valid for the purpose of the analysis.

Table 3. List of the observatories used in the analysis of Port Stanley *K*-indices. (Quasi-Dipole coordinates are given for 2011.0)

Name	Code	Geographic Coords		Quasi-Dipole Coords		Lower *K*=9 Limit (nT)	Time zone UT
		Latitude	Longitude	Latitude	Longitude		
Port Stanley	PST	-51.70	302.11	-38.90	10.81	328	-4
Tuscon	TUC	32.17	249.27	39.39	315.92	350	-7
Bay St.Louis	BSL	30.35	270.36	40.73	341.79	350	-6
Hermanus	HER	-34.42	19.23	-42.51	84.14	300	+1
Gnangara	GNA	-31.80	116.00	-43.42	187.75	450	+8
Canberra	CNB	-35.32	149.36	-45.05	227.32	450	+10
Trelew	TRW	-43.24	294.68	-30.25	5.15	286	-4
Argentine Islands	AIA	-65.24	295.74	-50.72	9.35	500	-4
Hartland	HAD	51.00	355.52	47.32	74.44	500	0

5.1 Analysis: Similar Geomagnetic Latitude

We considered the distribution of *K* values for observatories of similar geomagnetic latitude for a geomagnetically quiet (2008) and disturbed (2003) year. We used the observatories Tuscon (TUC) and Bay St.Louis (BSL) in the United States, Hermanus (HER) in South Africa, Gnangara (GNA) and Canberra (CNB) in Australia, and Hartland (HAD) in the United Kingdom. Although the difference in HAD geomagnetic latitude to PST was greater than the other observatories, we included this observatory's *K* indices in the analysis since they are derived using the same algorithm as we use for PST.

Figure 4 shows the distribution plots for 2003 and 2008. As expected all observatories generally follow a similar trend with *K*=1 peaking in the quiet year and *K*=3 peaking in the active year. Considering the distribution of PST to the other selected observatories in both years, it appears that *K*=0, 2, 4 are too low and *K*=1, 3 are too

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[1] Quasi-dipole coordinates are very similar to corrected geomagnetic coordinates (CGM) in all areas except around the low-latitude Atlantic region where CGM coordinates are not well defined (Emmert, Richmond, & Drob, 2010).

high. However it is worth noting that there is generally an increased variation between all observatories at $K<4$. Further adjustment to λ^2 and λ_u^2 may improve the distribution. For example, it should be possible to adjust the parameters such that some of the $K=1$ occurrences become $K=2$ giving a smoother distribution. Further modification to the max-min threshold level may improve the distribution of $K=3, 4, 5$.
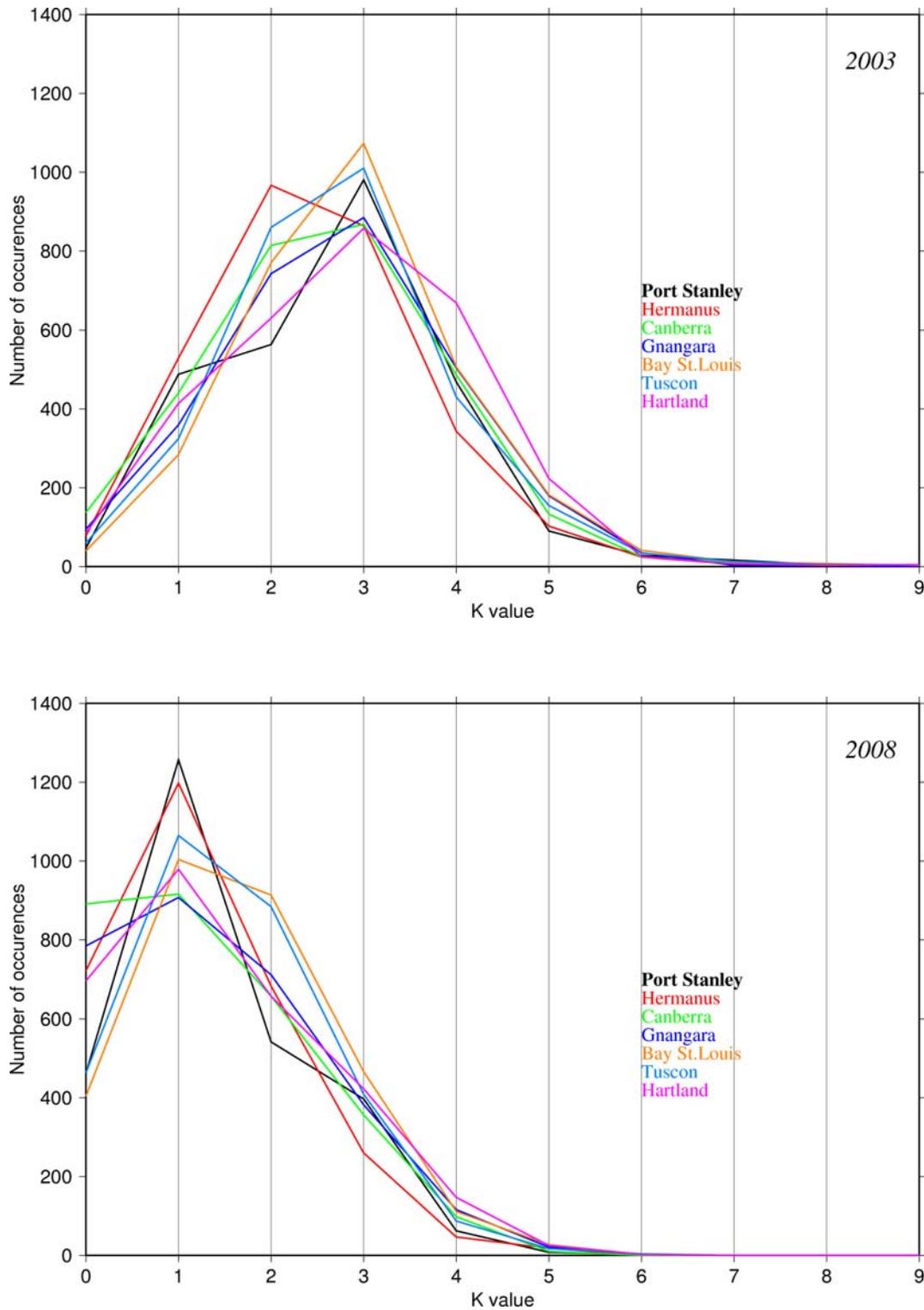
Figure 4. Distribution of K values during 2003, a geomagnetically active year (top plot) and during 2008, a geomagnetically quiet year (bottom plot) for seven selected observatories. PST is in black.

5.2 Analysis: Similar Time Zone

To examine the effect of seasonal and UT weighting and to check for any unexpected biases in the PST indices, we compared the general distribution of K values in each three-hour range and by direct comparison with nearby observatories. We considered the distribution of K values for each three-hour range for three nearby observatories for all data over four years between 2004 and 2007. Data from TUC, Trelew (TRW), and Argentine Islands (AIA) were compared with PST. Figure 5 shows two example plots: one for a daytime period (15-18 UT) where UT weighting had been applied and one for a night time period (21-24 UT) where no UT weighting was applied. There is some variation between the observatories during daytime hours, which is indicative of the difficulty previously discussed of establishing the perfect S_R curve. There will be differences in the K derivation methods used for each of the observatories compared, and there is also real variability of S_R and disturbance levels at these positions. During the night hours the distributions show a better match.

Furthermore we directly compared individual indices from PST with those from nearby TRW and AIA observatories for a number of years (AIA 2003-2009, TRW 2004-2007). Figures 6 and 7 show the differences computed for 2006. The histograms show the percentage occurrence where there is perfect agreement and where they differ by ±2 and ±1. We examined the results as a function of K value, three-hour period, and season. Overall the fit to both TRW and AIA appears to be reasonably good. However, the PST indices are more often less than those at TRW, which is not expected, since TRW is located to the north of PST. This bias is more pronounced for $K<4$, indicating a possible over-fitting of the S_R curve. Overall there is no bias between the AIA and PST indices; however, there is a clear bias during UT periods 15-18 and 18-21. The results show that PST is more often greater than AIA during these periods, which again could be investigated further.
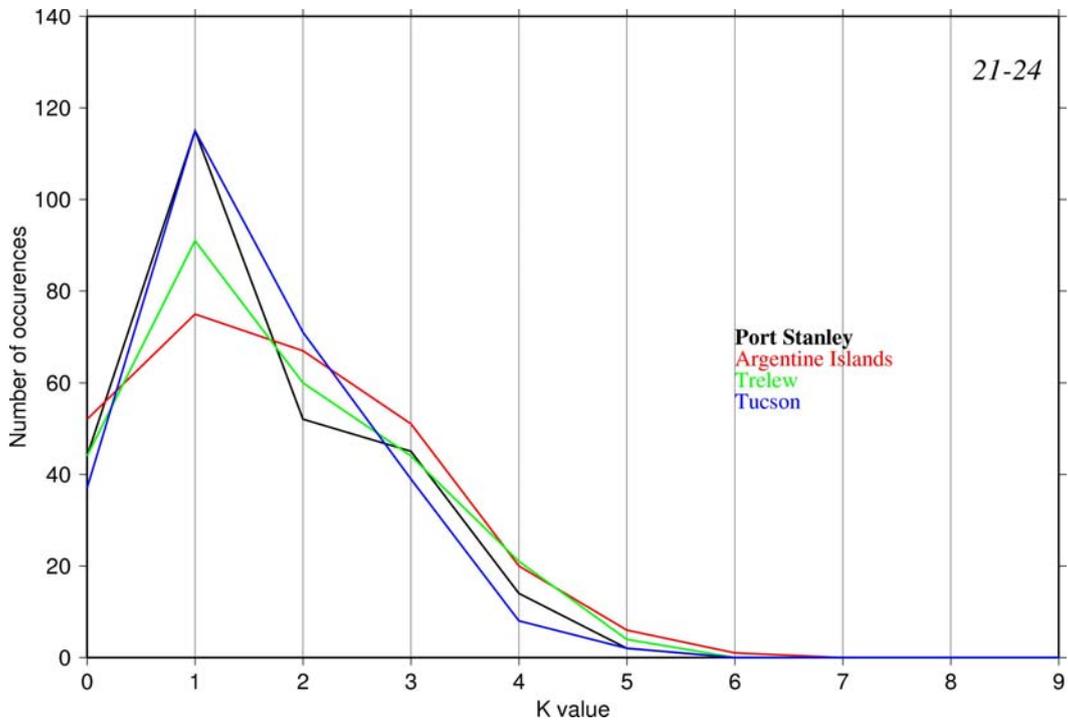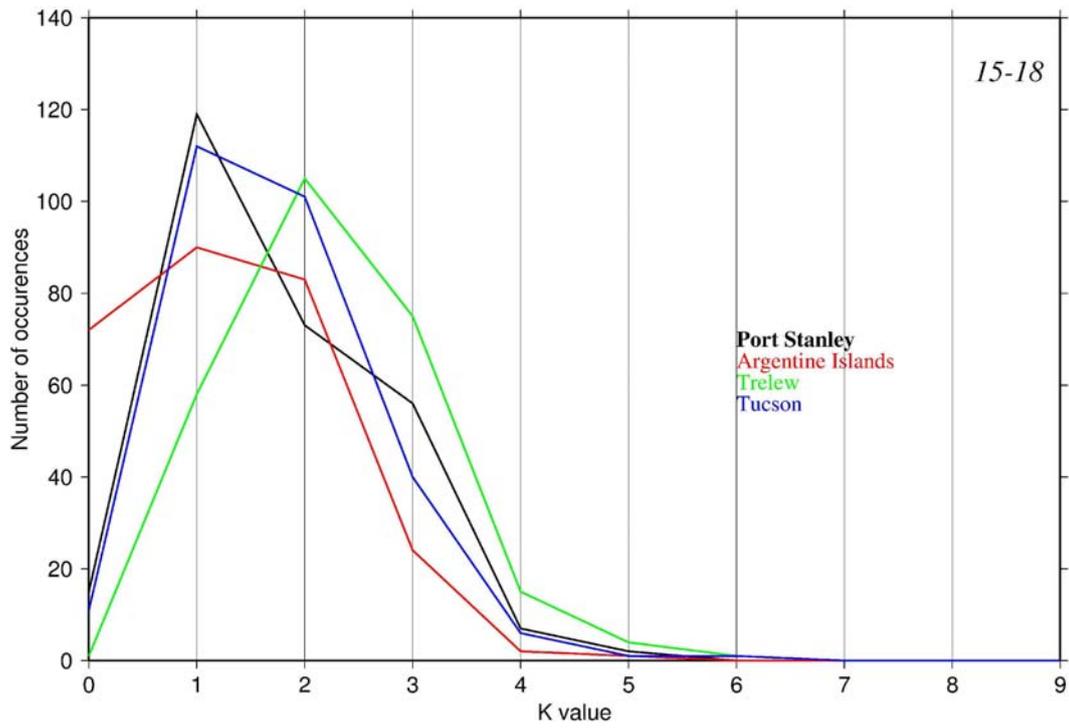
Figure 5. Distribution of *K*-indices during two selected three-hour time periods for observatories in a similar time zone to PST (AIA, TRW, and TUC) for 2004-2007. The top plot shows the distribution during a day-time period (15-18 UT), and the bottom plot shows the distribution during a night-time period (21-24 UT).
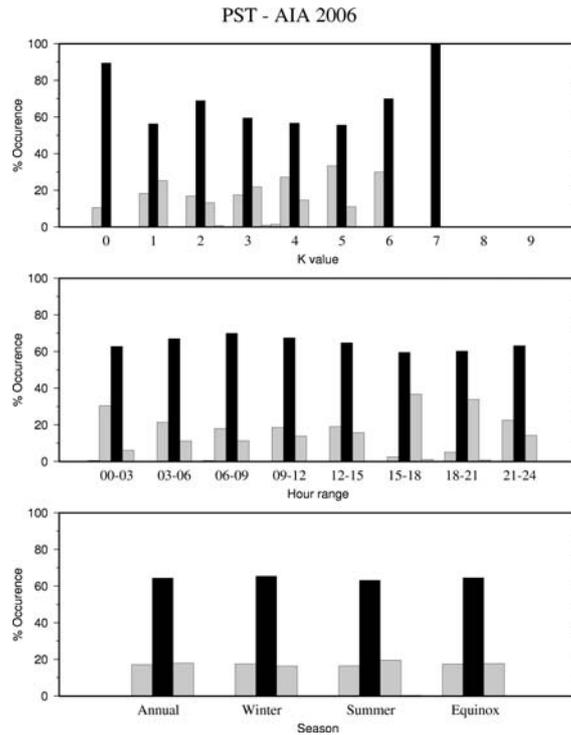
Figure 6. Differences between the *K* indices from PST and AIA in the sense (PST-AIA) for 2006. The histograms show the % occurrence where the indices agree (black) and % occurrence where they differ by ±2 and ±1 (grey, - to left, + to right). The top panel shows the comparison for each value of *K*, the middle panel shows the comparison for each 3-hour period, and the bottom panel shows the results as a function of season.
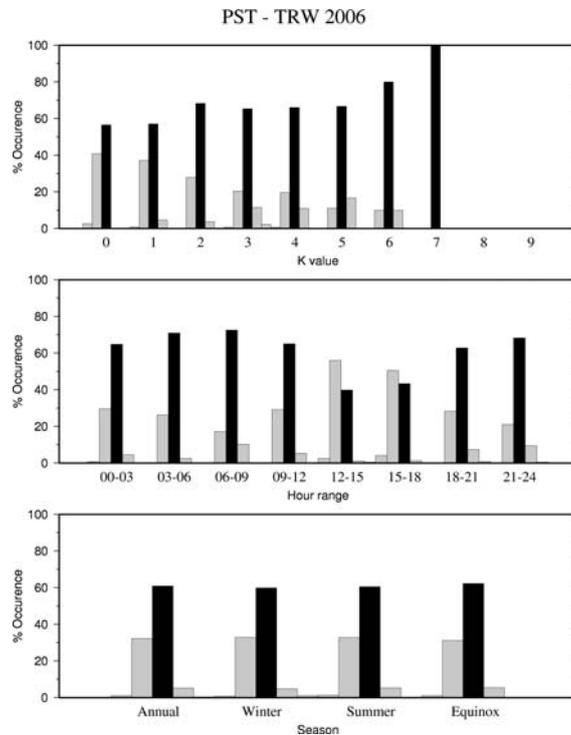
Figure 7. Differences between the *K* indices from PST and TRW in the sense (PST-TRW) for 2006. The histograms show the % occurrence where the indices agree (black bars) and % occurrence where they differ by ±2 and ±1 (grey, - to left, + to right). The top panel shows the comparison for each value of *K*, the middle panel shows the comparison for each 3-hour period, and the bottom panel shows the results as a function of season.

6   CONCLUSIONS

It has been shown that automatic derivation of PST K indices is now possible and the values produced are a reasonable match to the published indices from the two nearest observatories. In addition, the occurrence distribution of the PST K indices is comparable to those observed at other sites where geomagnetic activity levels are likely to be similar. It may be possible to improve the distribution of K=0, 1, 2 by modification of λ^2 and λ_u^2, the distribution of K=3, 4, 5 by modification of the max-min threshold, and UT weights by further analysis with observatories in the same time zone. This work is ongoing, and once the final parameters have been determined, the K indices will be computed for PST from 1994 and made available on-line. The process will also be repeated for the other BGS South Atlantic observatories: Ascension Island, where K indices from 1992 will be computed, and South Georgia, a new observatory currently being installed by BGS very close to the site of the original South Georgia observatory operated until 1982 by the British Antarctic Survey.

Currently the K derivation algorithm requires a full day of data from 0000 - 2359 UT. This restricts the derivation of the indices in real time using this method. Further development will be carried out to adapt the algorithm to work with the previous 24 hours of data and thus will not be constrained to running only once per day. This will enable the derivation of near real time K indices and thus enhance the quality and reliability of planetary real time quick-look indices.

7   ACKNOWLEDGEMENTS

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