Historical solar Ca II K observations at the Kyoto and Sacramento Peak observatories

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Abstract. Archives of full-disc solar Ca II K observations covering even short periods of time can offer important data to fill observation gaps and to allow a better transition from historical to modern data. Two examples of such archives are those from the Kyoto and Sacramento Peak observatories. As most other historical Ca II K data, they suffer from artefacts that need to be accounted for to derive accurate plage areas. Here we present the results of our analysis of these archives of solar Ca II K images.

1. Introduction
Archives of full-disc solar Ca II K solar observations are an important resource for solar activity studies. This owes to the reported relation between the Ca II K brightness and the magnetic field strength \cite{1} and the availability of Ca II K data for times not covered by magnetic field measurements \cite{2}. Historical photographic Ca II K observations are stored at various sites around the globe. Over the past years, the most prominent ones were digitised, e.g. those from the Arcetri \cite{3}, Kodaikanal \cite{4}, Mt Wilson \cite{5}, and Rome \cite{6} observatories. The availability of historical Ca II K observations in digital form allowed for new studies of the evolution of solar magnetism. We have developed a method to automatically analyse images from diverse archives and shown it to be more efficient than other methods in the literature \cite{7, 8}. We have also derived the first composite of plage areas covering the period 1893–2018 by consistently processing 9 archives \cite{8}. Even with 9 archives, however, there are still days without any observation. Furthermore, the quality of the analysed historical Ca II K data was found to deteriorate with time \cite{8}, thus making a link to the modern CCD-based data more difficult. To improve the composite and fill observational gaps, we have analysed the archives from Kyoto (Ky) and Sacramento Peak (SP) sites to determine plage areas.

2. Data and methods
While our focus here is on the Ky and SP observations, for comparison we also use the plage areas from the 8-bit Kodaikanal (Ko) and Rome (taken with the Precision Solar Photometric...
Figure 1. Examples of excluded Ky observations from our analysis. Image credit: Kwasan Observatory, Kyoto University.

Telescope, Rome/PSPT) archives [8] and the sunspot areas [10]. The Ko, Ky [11], and SP [12] observations were performed with a spectroheliograph over the period 1904–2007 (however, here we use the 8-bit digitisation of this archive, which includes only the data over 1907–1999), 1928–1969, and 1960–2002, respectively. The Rome/PSPT data were taken with a CCD camera over the period 1996–2018. There are 7546 and 7759 digital images from the Ky and SP archives, respectively, out of which we kept 3118 and 7755 for our study. The discarded images exhibit strong distortions and severe inhomogeneities; examples of which are shown for the Ky archive in Fig. 1. The number of images per year from the Ky and SP archives can be seen in Fig. 2. The Ky and SP we use (in total) cover 2305 (4338) and 6672 (6676) days, respectively. The Ky data have an average pixel scale of 2′′, while SP 1.2′′.

The SP observations were acquired at the Evans facility at Sacramento Peak. The archive of SP observations includes JPG files derived from the digitisation of the original photographic plates and FITS files of a sub-sample of the original data after some processing by [12]. This included re-sampling of the observations to account for the solar disc eccentricity [12]. Fig. 3 shows the solar disc eccentricity measured on the raw JPG SP data. The eccentricity lies between 0.3 and 0.4 before 1975, decreases to roughly 0.1 afterwards, and increases to 0.3 again in 1997. The disc eccentricity measured on the Ko and Rome/PSPT data are lower than those from the SP, being on average ∼ 0.1 and ∼ 0.05, respectively. Over 1980’s, however, SP data have a disc eccentricity that is comparable or even slightly lower than that in the Ko data. As a first step, we corrected raw JPG SP data for the disc ellipticity. For this, we detected the limb as described in [8,13], but then fitted an ellipse instead of a circle. The values of the semi-major and semi-minor axes were stored in the file header. The images were then resampled such that
Figure 2. Number of images per year within the Ky (solid orange for used, dashed red for excluded) and SP (solid blue for used) archives.

Figure 3. Solar disc eccentricity as a function of time from the SP (blue), Ko (red) and Rome/PSPT (black) data. The solid line shows annual median values, while the shading marks the asymmetric 1σ intervals.

the two axes of the ellipse were equal. Examples are shown in Fig. 4 along with the images processed by [12] to circularise the disc. Fig. 4 clearly demonstrates various artefacts introduced by the processing by [12], while the ellipticity appears to have been accounted accurately with our method.

The Ky archive consists of observations performed at the Kwasan and Ikoma observatories for the periods before and after 1941 [11]. The Ky observations have a persistent type of artefact in the form of dark or bright arcs over the solar disc (see Fig. 5).

All archives were processed to perform the photometric calibration (except for the Rome/PSPT which have been taken with a CCD and do not require it) and compensate for the limb darkening with the methods presented by [7, 8]. Examples of the processing steps applied on Ky and SP observations are shown in Fig. 5, showing that our processing is able to account for most of the artefacts affecting these observations.
Figure 4. Raw SP observations taken on 14/10/1965 (1st row) and 21/01/1967 (2nd row) prior (left column) and after the circularisation of the disc with our method (middle column) and that by [12] (right column). All images are shown to their entire range of values. The white circles denote our estimate of the solar radius as determined on the images after circularisation (middle column). Artefacts introduced by the processing of [12] to circularise the disc are evident in the right column.

3. Plage areas

We determined plage areas from the Ky and SP archives with the same method as in [8], which singles out plage regions with a contrast threshold of a multiplicative factor to the standard deviation of the intensity at quiet Sun regions. Example masks of identified plage regions in the Ky and SP data can be seen in the last column of Fig. 5, while in Fig. 6 we show the evolution of the fractional plage areas determined from the various analysed archives. The areas from SP are greater than from all other archives. This is consistent with the use of a narrower bandwidth at SP (0.5 Å) than at Ky and Rome/PSPT (0.7 and 2.5 Å, respectively) observatories, but not with Ko which has the same nominal bandwidth as SP. Issues concerning the Ko data after 1980 have been discussed by [8, 13]. However, SP plage areas are even higher than those from Ko for the entire period covered by SP, suggesting that there might also be an inconsistency with the SP data. We note that the contrast of the plage and network regions is higher in the SP images than in Ky (see Fig. 5) or Ko ones. This suggests that the bandwidth information for the SP and Ko archives might not be correct. The plage areas from Ky are at a similar level but slightly lower than those from Ko, which is consistent with the bandwidths used at those sites. We notice the ranking of the solar cycles in the various plage series to be the same as in the sunspot areas, with the exception of solar cycles 21 and 22 in Ko and SP data. The ratio of sunspot to plage areas depends on the activity level for both Ky and SP series. In particular, for the Ky series it is ∼20 over solar cycle 17 and decreases to ∼13 over cycle 19. Similarly for the SP series, the ratio is ∼55 over cycle 20 and reaches the value ∼35 over cycles 21 and 22.
Figure 5. Examples of processing steps applied on Ky (1st and 2nd rows) and SP (3rd and 4th rows) observations taken on 17/04/1956 (1st row), 28/12/1966 (2nd and 3rd rows), and 21/01/1967 (4th row). Columns are: original raw density image, computed background of the image, photometrically calibrated and limb-darkening-compensated image, and segmentation mask. The raw density images and the backgrounds are shown to the entire range of values within the disc of the original image, the calibrated images are shown in the range [-0.5,0.5], while the masks show plage regions in orange and QS and network regions in blue. The images are not compensated for ephemeris.

4. Summary
We have processed the Ca II K archives from observations of the Ky and SP archives. This allowed us to determine the evolution of plage area from the Ky and SP observations. The results we acquired can be used to fill gaps in the plage time-series from the other available archives. In particular, there are 82 and 893 days with observation in the archives of Ky and SP, respectively, which were not covered by any archive analysed by [8]. Only 3 of those days are common in the observations from Ky and SP archives. Furthermore, the use of those archives can potentially allow for a better transition from historical to modern CCD-based data taken since late 1980’s. A more detailed description of the analysis of the Ky and SP archives and an
Figure 6. Derived plage areas from the Ky (solid red), and SP (solid blue) archives as a function of time. Individual dots (lines) denote daily (annual) values. Also shown are annual values of plage areas from the Ko (dashed orange line) and Rome/PSPT (dashed black line) archives as well as the sunspot areas by [10] multiplied by 20 (dashed green line).

update of the plage area composite by [8] with the new data will be the focus of a forthcoming paper [9].

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