Differential coronal rotation using radio images at 17 GHz

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ABSTRACT
In the present work, we perform time-series analysis on the latitude bins of the solar full disc (SFD) images of Nobeyama Radioheliograph (NoRH) at 17 GHz. The flux modulation method traces the passage of radio features over the solar disc and the autocorrelation analysis of the time-series data of SFD images (one per day) for the period 1999–2001 gives the rotation period as a function of latitude extending from 60°S to 60°N. The results show that the solar corona rotates less differentially than the photosphere and chromosphere, i.e. it has smaller gradient in the rotation rate.

Key words: Sun: corona – Sun: radio radiation – Sun: rotation.

1 INTRODUCTION
In the recent studies of the solar rotation, the tracer methods were extensively used for the determination. The features like sunspots, plages, filaments, faculae, bright points, super granules, coronal holes, giant cells etc. were found to rotate with the Sun (Howard 1991, 1996; Shivraman et al. 1993). By tracing the passage of any of these features over the solar disc, one can estimate the rotation as well as its differential nature with respect to height and latitude. In general, the equatorial region rotates faster than the polar region. The solar coronal rotation is a comparatively less understood phenomenon because the coronal features are less prominent in both the time duration and spatial extent. The observations are affected by the fact that the solar corona is optically thin across a wide range of observed radio frequencies. Recent studies of the solar radio emission provided a lot of information concerning the solar corona (Vats et al. 1998; Mehta 2005). The radio observations have the advantage of permitting one to attain resolution for the heights in the corona as the propagation of radio waves distinctly depends on the plasma density in the corona. By using radio flux data at different frequencies (Vats et al. 2001), it has been shown earlier that the coronal rotation depends faster than the polar region. The solar coronal rotation is a comparatively less understood phenomenon because the coronal features are less prominent in both the time duration and spatial extent. The observations are affected by the fact that the solar corona is optically thin across a wide range of observed radio frequencies. Recent studies of the solar radio emission provided a lot of information concerning the solar corona (Vats et al. 1998; Mehta 2005). The radio observations have the advantage of permitting one to attain resolution for the heights in the corona as the propagation of radio waves distinctly depends on the plasma density in the corona. By using radio flux data at different frequencies (Vats et al. 2001), it has been shown earlier that the coronal rotation depends faster than the polar region.

Several groups have reported from time to time that the solar corona rotates differentially, with respect to latitude, in the same way as the photosphere and the chromosphere. The analysis of X-ray bright points (XBPs) in SOHO/EIT (Solar and Heliospheric Observatory/Extreme ultraviolet Imaging Telescope) images (Brajša et al. 2001, 2002, 2004; Karachik, Pevtsov & Sattarov 2006), and recent analysis of XBPs in Hinode/XRT (X-Ray Telescope) and Yohkoh/SXT (Soft X-ray Telescope) images (Kariyappa 2008) also asserts the coronal differential rotation. However, in contrast to these references, Weber et al. (1999) and Weber & Sturrock (2002) studied the rotation rate of corona by using Yohkoh/SXT data and showed that the soft X-ray corona does not exhibit any significant differential rotation, i.e. the corona rotates more rigidly than the chromosphere and the photosphere. Recently, by making use of XBPs observed with the Yohkoh/SXT, Hara (2009) found that the rate of differential rotation changes with a parameter Δt which is linked with the lifetime of XBPs. The long-lived XBPs follows the rotation rate of the photospheric magnetic field, whereas, the short-lived XBPs approaches to that evaluated from the photospheric Doppler measurements.

Zaatri et al. (2009) compared differential rotation of subphotospheric layers derived from GONG+++ dopplergrams with the small bright coronal structure (SBCS) observed through SOHO/EIT for the period correspond to the declining phase of solar cycle 23. They reported that the SBCS rotate faster than the upper subphotospheric layer (3 Mm) by about 0.5 d−1 at the equator. The latitude gradient of the rotation rate of the SBCS and the subphotospheric layers were found to be very similar.

The comparison of the data of the solar magnetic elements reveal that the differential rotation of the compact magnetic elements with negative and positive polarities have similar behaviour for the solar cycles 20 and 21 (Japaridze, Gogolashvili & Kukhianidze 2009). It is also established that some variations in the rotation rate of compact magnetic elements were present at the time of polarity reversal of the Sun.

The differential rotation of the solar corona is, therefore, still an open subject and further studies are required to establish the coronal differential rotation. Here we report the study of the coronal rotation using Nobeyama Radioheliograph (NoRH).
2 OBSERVATIONS AND METHODOLOGY

The NoRH at 17 GHz consist of an array of 84 antennas aligned in the T-shaped configuration. This is dedicated only for the solar observations. High speed processing of signals from all antennas generates full disc radio images of the Sun, at the maximum rate of 20 images s\(^{-1}\). The Sun is observed for 8 h d\(^{-1}\). The radioheliograph provides unprecedented uniform sampling of solar full disc (SFD) images with high spatial and temporal resolutions of 10 arcsec and 50 ms, respectively (Shinzo 1995). The observations are possible throughout the year without any interruption by weather conditions. The radio images seem to discriminate low contrast or faint structures on the solar disc e.g. dark filaments, bright points, coronal holes and other large-scale structures.

Here, we analyse the SFD images obtained from NoRH at 17 GHz. Each image is of 512 \times 512 pixel in size. The principal technique of our investigation is to calculate the autocorrelation coefficient of the intensity variation for a set of latitude bins selected on the NoRH images. For this we utilize one NoRH full disc image per day on which latitude bins, or strips, are chosen. The dimensions of these rectangular bins are just 2 pixels in width and the length is such as to incorporate the entire pixels on the solar disc image at each latitude. The strips are selected at every 10° latitude.

For each latitude, a time-series of the radio intensity is generated from the average of the selected pixels values in the strip. To determine rotation period, we obtained autocorrelation coefficient using the standard subroutines of IDL software. The period estimation is a straightforward identification of any dominating periodically varying signal present in the coronal radio emission.

3 DATA ANALYSIS

For the time-series of each latitude, autocorrelation up to a lag of 145 d is calculated and plotted in the form of autocorrelogram. The typical autocorrelogram for a data set for the year 1999 at 30°N latitude is shown in Fig. 1. A systematic periodic modulation can be seen from the autocorrelogram as a modulation due to the solar rotation. The autocorrelation coefficient at some of the latitudes is quite high and the curve is quite smooth showing many damped cyclic oscillations (Fig. 1). The amplitude of oscillatory features reduces perhaps due to the temporal variability in the solar rotation. This is because of the long-term persistence of the solar features on the solar disc at that latitude. The short-term features at higher latitudes affect adversely the smoothness, numbers of cyclic variation as well as the magnitude of autocorrelation coefficient. Nevertheless, the first peak of each autocorrelogram is quite clear and could be used for the estimation of the synodic rotation period up to ±60° latitude. The average radio flux at higher latitudes (>60°), in both the hemispheres, does not show periodic nature and hence is not used for obtaining rotation periods. Thus from NoRH images we are able to get rotational periods from 60° S to 60° N only. The radio emission at higher latitudes is either uniform or totally random as a function of time. Employing this method, we determined first the synodic rotation period and then from the synodic the sidereal rotation period, at every 10° latitude in the range of ± 60° each year during 1999–2001.

To compare the sidereal rotation rate \(\Omega(\psi)\) of this work with other observations and their models of the solar rotation, we fit the data using the standard polynomial expansion in its most commonly used form, as given below

\[
\Omega(\psi) = A + B \sin^2 \psi,
\]

(1)

where \(\Omega(\psi)\) is the sidereal rotation rate at heliographic latitude \(\psi\). The parameter \(A\) represents the equatorial rotation rate and \(B\) represents differential rate largely at low latitudes. Since we have not used the data of the higher latitudes >60° on both the sides of the equator, hence, it is sufficient to use only the first two terms of the standard polynomial expansion (Beck 1999).

The rotation rate is related to the rotation period as given below:

\[
T(\psi) = \frac{360°}{\Omega(\psi)},
\]

(2)

where \(T(\psi)\) is in day and \(\Omega(\psi)\) in degree per day.

4 COMPARISON

The estimated sidereal rotation period has been plotted as a function of the latitude for the years 1999–2001, separately. Figs 2–4 represent the differential rotation profiles of each year. In spite of scatter in the data points, the solar differential rotation is clearly evident. We obtained the coefficient \(A\) and \(B\) of the solar coronal rotation for each year separately. These are tabulated in Table 1. The mean of these has been compared with the results obtained through the analysis of Hinode/XRT XBP, Yohkoh/SXT XBP (Kariyappa 2008) and SOHO/EIT coronal bright points (CBPs) data (Brajša et al. 2004).

The sidereal equatorial rate (coefficient \(A\), in Table 2) in the case of NoRH is found to be 4.4 per cent higher than the
Figure 2. The coronal sidereal rotation period as a function of the latitude for the year 1999.

Figure 3. As in Fig. 2 for the year 2000.

Figure 4. As in Fig. 2 for the year 2001.

Hinode/XRT XBPs (14.2 ± 2 d\(^{-1}\)) and 15.8 per cent lower than the Yohkoh/SXT XBPs data (17.6 d\(^{-1}\)), on average. Coefficient \(A\) of the present work is found to be comparable with the sunspot data (14.6 d\(^{-1}\)) and SOHO/EIT CBPs data (14.7 d\(^{-1}\)). The differential rate represented by coefficient \(B\) is found to be significantly lower than the values obtained by Kariyappa (2008) using Hinode/XRT XBPs data (49.4 per cent) and Yohkoh/SXT XBPs data (53.1 per cent), Brajša et al. (2004) using SOHO/EIT CBPs data (31.3 per cent) and Balthasar, Vázquez & Wöhl (1986) using photospheric sunspots data (25.8 per cent). It means the latitude gradient of the coronal rotation rate is much lower at 17 GHz radio frequency in comparison to that obtained from the observations of X-ray and extreme ultraviolet (EUV) frequencies.

From the analysis of radio flux at 2.8 GHz, Mehta (2005) could not find any systematic relationship between coronal rotation period and phases of solar cycle. Our results show comparatively faster equatorial rotation in the year 2000, than those of 1999 and 2001. Thus, it may have some relation with the maxima of the solar activity in the 23-d cycle. The sunspot numbers in 1999 and 2001 are relatively lower than 2000. The estimated coefficients \(A\) and \(B\) from the Nobeyama radioheliogram show a temporal variability. The temporal variations of \(A\) and \(B\) and sunspot numbers are shown in Fig. 5.

### 5 CONCLUSION

Our results for coefficient \(A\) are more in agreement with the results derived from the sunspot region at the photospheric (Howard, Gilman & Gilman 1984; Balthasar, Vázquez & Wöhl 1986; Pulkkinen & Tuominen 1998) and at the chromospheric level (Brajša et al. 2004; Karachik et al. 2006). Since Yohkoh/SXT observed the soft X-ray emission of the corona and was not a coronograph, the portion of corona that was imaged through this SXT range from the photosphere to a height of approximately 0.5 \(R_\odot\) (David McKanzie, private communication). Whereas, the radio emissions at 17 GHz originate approximately at the altitude of \(\sim 1.2 \times 10^4\) km above the photosphere. The height is adopted from Vats et al. (2001), wherein the enhanced electron density model by Aschwanden & Benz (1995) was used to estimate the average altitude. Thus 17 GHz seems to originate almost at the interface of the chromosphere and the corona, hence, the equatorial rotation rate matches more with the photospheric or the chromospheric data rather than the coronal data. The analysis of daily SFD radio images at 17 GHz for the years 1999–2001 shows that the coronal equatorial rotation rate is higher than those obtained by XBPs and quite lower than those obtained by CBPs (Kariyappa 2008).

The coefficient \(B\) shows that the corona does rotate differentially as in the photosphere and chromosphere; but the gradient is lower (<25.8 and <31.3 per cent, respectively). This is in agreement with the results obtained by Weber et al. (1999) and Weber & Sturrock (2002). The difference in the rotation profiles of soft X-ray emission and 17 GHz could possibly be due to their different regions of origin in the solar atmosphere. The coefficients \(A\) and \(B\) are also compared

| Years | \(A \pm E_A\) | \(B \pm E_B\) | Annual sunspot numbers |
|-------|-------------|-------------|------------------------|
| 1999  | 14.826 ± 0.200 | −1.528 ± 0.474 | 093.3 |
| 2000  | 15.083 ± 0.239 | −2.892 ± 0.567 | 119.6 |
| 2001  | 14.543 ± 0.097 | −1.968 ± 0.229 | 111.0 |
| Mean  | 14.817 ± 0.060 | −2.129 ± 0.143 | 107.9 |

Table 1. The coefficients \(A\) and \(B\) obtained from NoRH at 17 GHz for the years 1999–2000. The last column gives annual sunspot numbers.
Table 2. The coefficients $A$ and $B$ obtained from the present work and other recent published results.

| Data source     | Tracers     | $A \pm E_A$          | $B \pm E_B$          | References                  | Period          |
|-----------------|-------------|----------------------|----------------------|-----------------------------|-----------------|
| NoRH Flux       | modulation  | 14.817 ± 0.060       | −2.129 ± 0.143       | Present work                | 1999–2001       |
| Hinode/XRT      | XBPs        | 14.192 ± 0.170       | −4.211 ± 0.775       | Kariyappa (2008)            | 2007 January, March and April |
| Yohkoh/SXT      | CBPs        | 17.597 ± 0.398       | −4.542 ± 1.136       | Kariyappa (2008)            | 1992–2001       |
| SOHO/EIT        | CBPs        | 14.677 ± 0.033       | −3.100 ± 0.140       | Brajša et al. (2004)        | 1998 June–1999 May |
| Greenwich Sunspots |           | 14.551 ± 0.006       | −2.870 ± 0.060       | Balthasar et al. (1986)     | 1874–1976       |

Figure 5. The coefficients $A$ and $B$ and annually averaged sunspot numbers for 1999–2000.

with the annual sunspot numbers (see Table 1). This gives evidence of the dependence of coronal rotation on the phases of solar cycle.

Fig. 5 shows that the coronal equatorial rotation ($A$) is in phase with the annual sunspot number, whereas its latitude-dependent differential gradient is antiphase to the annual sunspot number. A long-term study is indeed required to ascertain this correlation more clearly.

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