Correction of Systematic Error in Nobeyama 17 GHz (R+L) Radio Flux

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Data Selection

The polar fields measured at WSO are measured as the average flux through a 175”*175” aperture grazing the solar limb (on the inside) at the point where the limb is cut by the central heliographic meridian. The size of the aperture (~3’) is thus 1/11 of the solar diameter (1919”). Because the polar bright patches observed in the radio flux occur within ~1.5’ of the limb (only half the aperture), we have selected points of the radio image that lie between a pole and a line defined as pixel coordinate y_N = N pole - *radius*/11 for the Northern area and y_S = S pole + *radius*/11 for the South, using the *radius* (in pixels) rather than the diameter. This is a compromise in trying to match the magnetic measurements to the radio measurements. We have tried to use radio data from the poles all the way down to 3’ from the limb. The results are qualitatively similar except that the brightness enhancement signal is significantly reduced. A future refinement of the analysis would be to quantify the effect of varying the portion of the radio image used. The polar magnetic field reported by WSO is a 30-day average of all observations through the polar apertures, calculated every ten days, averaging out any variations within roughly a solar rotation. We analyze the Nobeyama average total radio brightness temparature data, *i.e.* R[ight polarization]+L[eft polarization], for each day using only pixel values higher than 9,900 K.

A Look at the Radio Data

Figure 1 shows *daily* values of the brightness temperature (T_B) as well as an 11-day running mean (heavier curves). There are several features that deserve notice:

1) A solar cycle variation with minimum when the polar fields reversed near 2001.0. This variation is large (~1000 K), much larger (and therefore easier to measure) than the brightness temperature excess found by *Tlatov et al.* [2005] from circular polarization Nobeyama data (R[ight]-L[left]).

2) Occasional observational defects (one day “spikes”). These can be, and are, removed automatically in the further analysis.

3) Occasional clear rotational modulation, *e.g.* in 1999, with period ~33 days.

4) A variation with the solar B_0 angle (heliographic latitude of the center of the disk) with the expected anti-phase of the two Hemispheres, excepting the time of polar field reversal and a few years thereafter (2000-2003) as is also seen in the B_0-variation of the polar magnetic fields.

5) Systematic differences (generally $T_BN > T_BS$) between the Hemispheres of the average level of the brightness temperature.

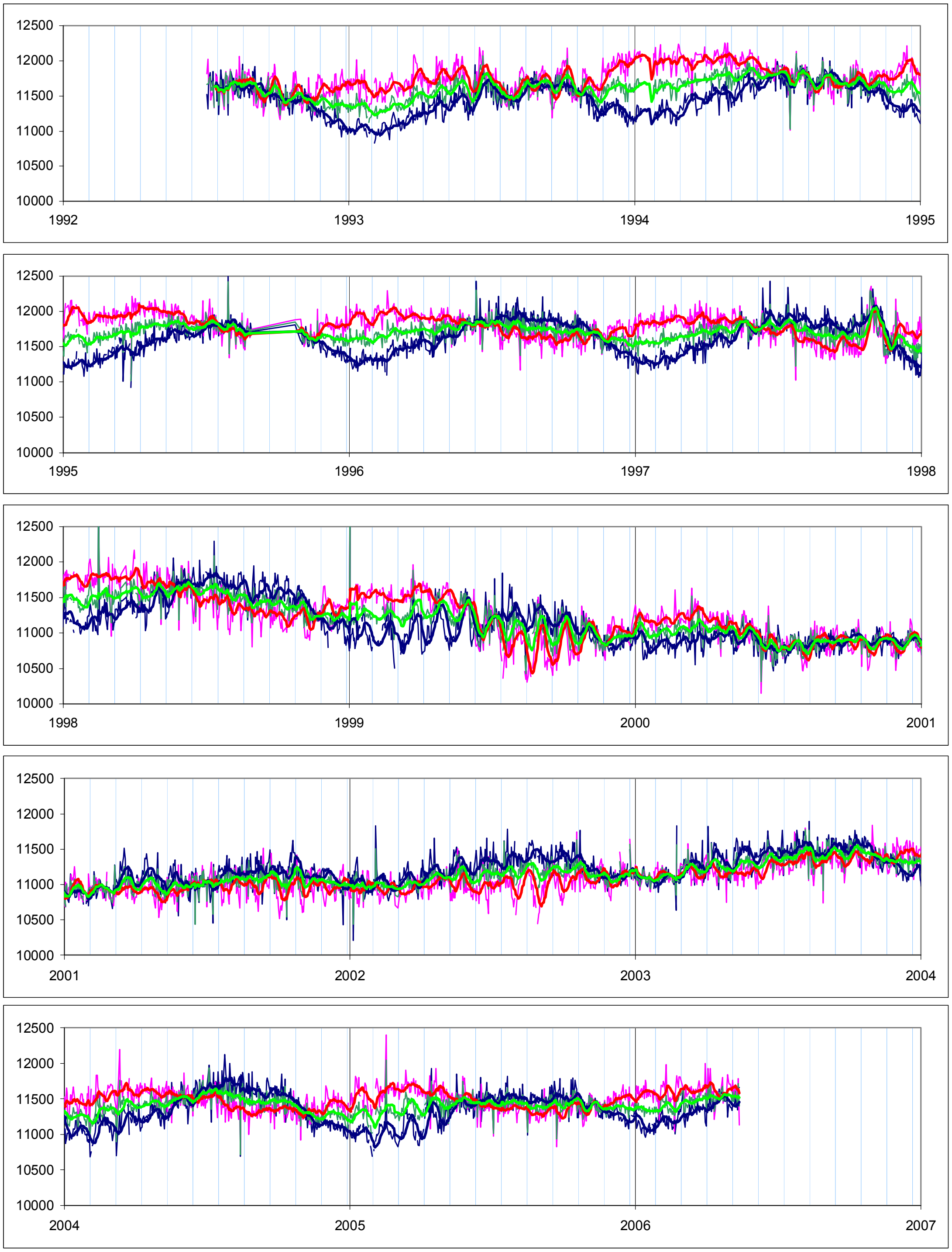

Figure 1. Daily values of Nobeyama 17 GHz (R+L) emission brightness temperature for the northern polar cap (blue), the southern polar cap (pink), and their average (green). 11-day running means (offset +11 days for better display of the underlying daily values) are shown with heavier lines and colors. The (light-blue) vertical gridlines are spaced 33 days (synodic rotation period at 60° latitude) apart.

Raw B_0 Modulation

Computing the difference between, say, the Northern Hemisphere and the Southern Hemisphere should eliminate most (but not all) of the solar cycle variation and show double the B_0 modulation, since the latter is in anti-phase between hemispheres. Figure 2 shows the result:

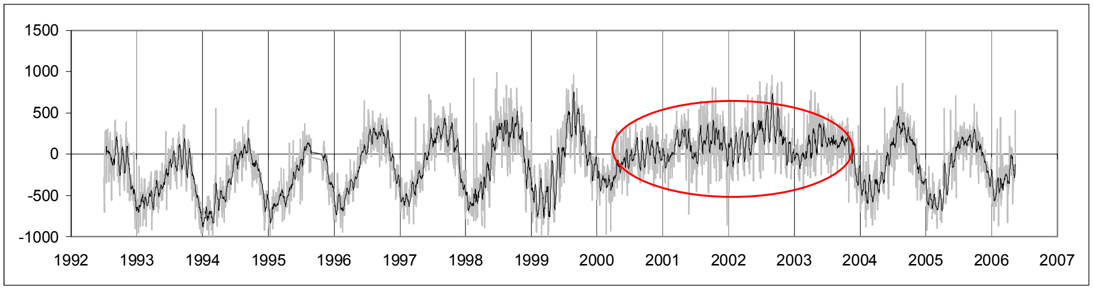

Figure 2. Difference, T_BN - T_BS, between daily values of the Nobeyama 17 GHz (R+L) emission brightness temperatures (light-grey curve). The 11-day running mean (offset 11 days as in Figure 1) is shown with a black line. The time of polar field reversal is indicated by the red oval.

Note how abruptly the modulation ends in early 2000 and how abruptly (after the Halloween storm?) in late 2003 it again begins. Let's review the polar field reversal process.

The polar field reversal is caused by unipolar magnetic flux from lower latitudes moving to the poles, canceling out opposite polarity flux already there, and eventually establishing new polar fields of reversed polarity. Because of the large aperture of the WSO instrument, the net flux over the aperture will be observed to be zero (the "apparent" reversal) about a year and a half before the last of the old flux has disappeared as opposite polarity flux moving up from lower latitudes begins to fill the equatorward portions of the aperture. The new flux is still not at the highest latitudes where projection effects are the strongest. The result is that the yearly modulation of the polar fields is very weak or absent for about three years following the (apparent) polar field reversal. Only after a significant amount of new flux has reached the near pole regions does the yearly modulation become visible again. This characteristic behavior is apparently also seen in the radio flux data.

A Digression: Nutation?

The B_0 angle is given to four decimal places in the FITS files for the radio maps. We also calculate B_0 and find that our values differ from the Nobeyama values at or below the 0.001-degree level. The disagreement changes during the year (out of phase for days six months apart) and also changes from year to year in a sinusoidal manner with a period of 18 to 19 years. Although such accuracy is not really needed nor warranted, we like to understand the data. The magnitude and phase of the difference suggest that either the Nobeyama B_0-values are not corrected for nutation of the Earth's axis or ours are overcorrected for the same, although by reviewing the code I fail to see how.

Superposed Epoch Analysis of B_0 Modulation

In order to get a clearer picture of the modulation we superpose the hemispheric difference for all year when the modulation was present with the beginning of the year as the key epoch. The result is shown in Figure 3.

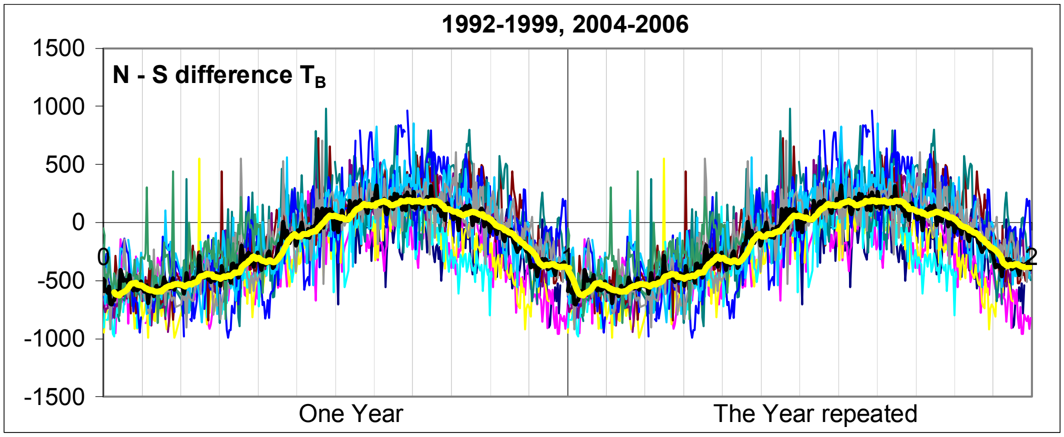

Figure 3. Difference in brightness temperature between the Northern polar cap and the Southern polar cap as a function of the day within the year. The yellow curve shows the average modulation while the numerous other colors represent one year's worth of data. The year is repeated once more to the right to better bring out the shape of the curves.

While the B_0 modulation is very clear, there is a definite phase shift of about one month towards earlier times. The minimum is in February rather than in March. Figure 4 shows the superposed epoch result for the interval 2000-2003 where the B_0 modulation was weak or absent.

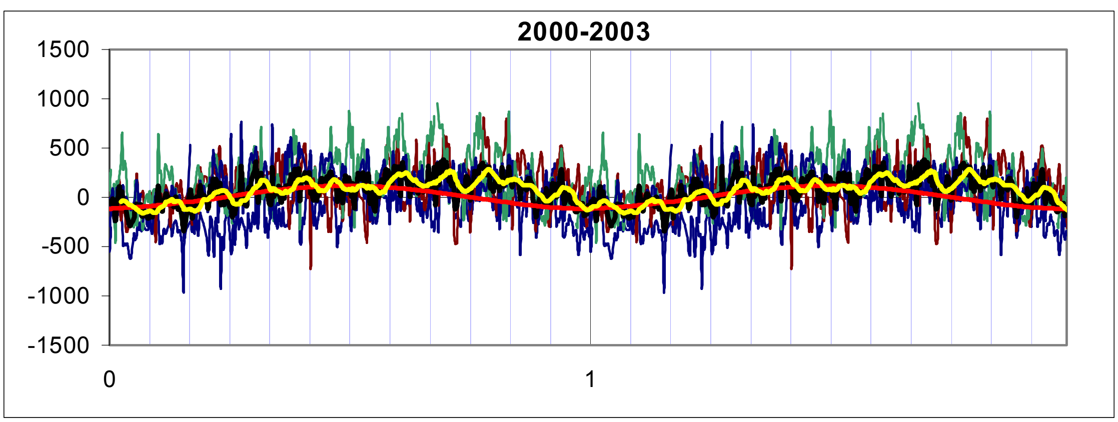

Figure 4. As Figure 3 except for the years 2000-2003. The red curve tracks the variation of the solar declination through the year (scaled to match the amplitude of the average difference curve.

Origin of the Phase Shift

If the phase shift relative to the variation of B_0 were due to some geometrical effect related to the position of the sun in the sky we would expect that it would be approximately the same for both solar polar caps (after all, the sun is a rather small object in the sky, ~1/100,000 of the visible sky) and therefore to cancel out when the difference between the hemispheres is formed. Apparently this does not happen, so we need to examine each polar cap separately. Figure 5 forms the basis for our discussion.

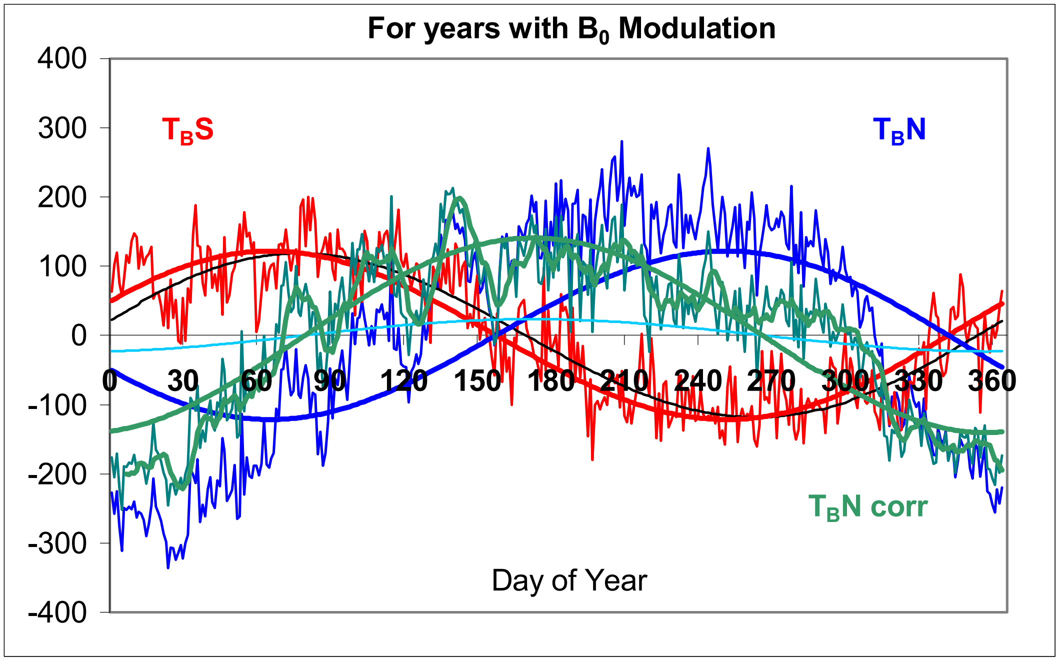

Figure 5. The red ragged curve is the average variation with day of year of T_B for the southern polar cap for years with strong B_0 modulation. The blue ragged curve is similarly the average variation of T_B for the northern polar cap. For all data in this Figure, the yearly mean for each year was first subtracted to compensate for the solar cycle variation of T_B. For the remaining curves see the text.

The smooth red curve in Figure 5 shows the function $f_S(t) = -16.8 * B_0(t)$. It is clear that this function is a good approximation to the variation of T_BS [an even better approximation is obtained by introducing a phase shift, $-17 * B_0(t+8.5$ days), as shown by the thin black curve next to the red one]. Encouraged by our result we assumed that the same function but with the opposite sign, $f_N(t) = -f_S(t) = +17 * B_0(t)$, might account for the variation of T_BN. As the smooth blue curve shows, this hope did not bear out, as the smooth blue curve is a poor fit to the ragged blue T_BN. If we assume, nevertheless, in analogy with T_BS, that T_BN *should* have the same B_0-dependence (albeit with the opposite sign) we can subtract $f_N(t)$ from T_BN to get the green ragged curve with its 11-day mean superposed showing what a residual that is *not* explained by a B_0-dependence. The green curve of residuals has a clear maximum in local summer and a clear minimum in local winter. This immediately suggests that there is a dependence on *solar* *declination*, δ. In fact, the smooth green curve is simply 6 * δ which provides a good fit to the residuals. In sum, we suggest that the variation of TB with time of year may be written (to first approximation)

$$\Delta T_B = a + b\, B_0 + c\, \delta$$

where the coefficients *a*, *b*, and *c* depend on the hemisphere and possibly on epoch as well. A least-squares fit to all years with a B_0-modulation yields the following values

Table 1

Quantity	North polar cap	South polar cap
a	-1.7581	6.8928
b	21.9883	-24.2070
c	7.4790	1.4193
R^2	0.91	0.80

The constant term, *a*, is small and not statistical significant and can be taken as zero. The smallness of *c* for the South explains why a small phase shift (8.5 days) works as well. Of course, when using the full expression with *b* and *c*, no phase shift is needed. It is not a surprise that the final fit yields slightly different coefficients than the trial coefficents used in Figure 5.

Figure 6 just serves as a reminder the variation with day of year of the three angles that are important for solar observations, the B_0-angle, the P-angle, and the solar declination:

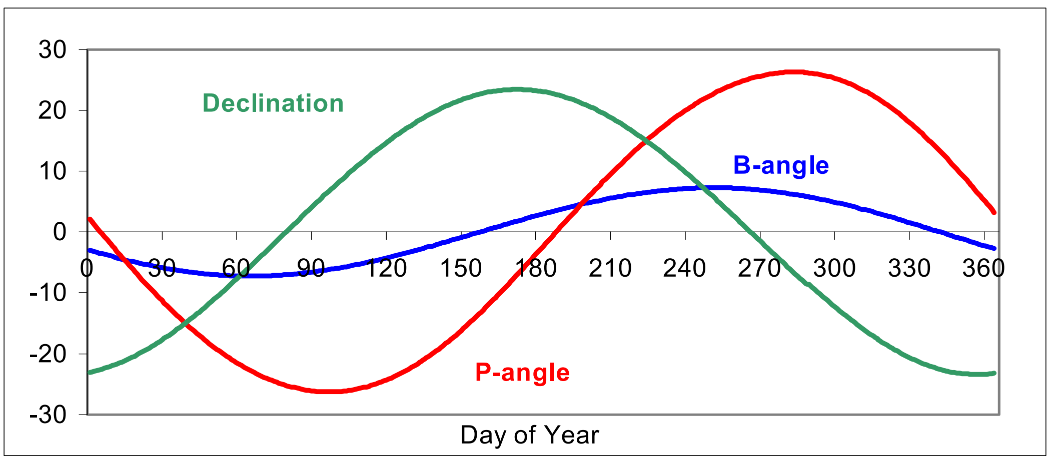

Figure 6. Yearly variation of B_0, P, and solar declination δ. Historically, P-angles for the sun are signed and lie in [-180:+180], rather than in the usual [0:360].

Because the phase difference between the B_0-angle and the P-angle is only about one month it is hard to disentangle a separate dependence on B_0 and P. Introducing P in the regression equation just moves a lot a variation from a B_0-dependence to make it look like a P-angle dependence. In the following section we apply the regression coefficients given in Table 1 to examine how closely we model the variations. We set *a* to zero as there is already year to year variations in the background level of T_B.

The Fit to the Yearly Variation

Figure 7 shows the yearly variation of TB for the years away from the polar field reversal. The upper panel shows the uncorrected data, while the lower panel shows the data corrected for declination as suggested above.

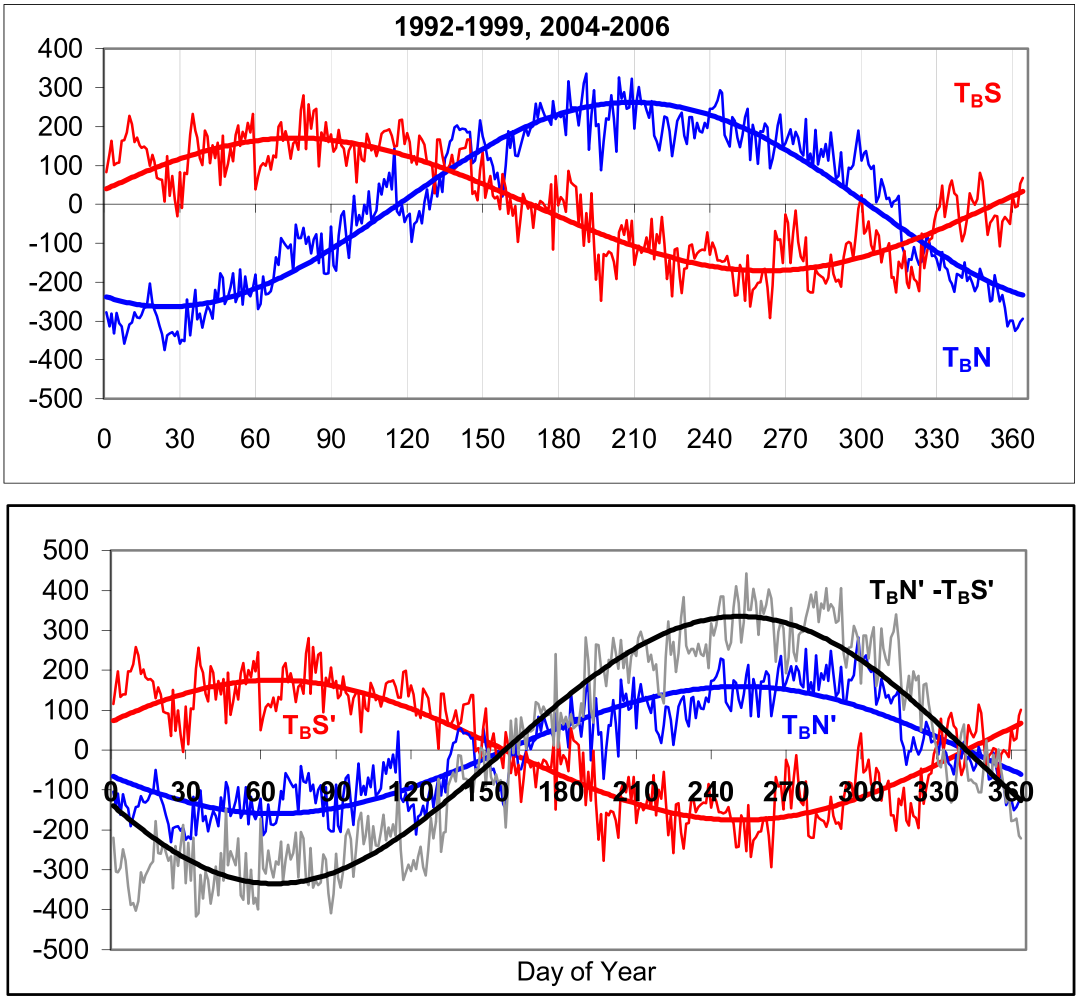

Figure 7. Yearly variation of T_B North and South for years with a clear B_0-modulation. The upper panel shows the uncorrected data, while the lower panel shows the data corrected for declination. The black curve shows the difference between North and South.

The difference between North and South is a measure of the B_0-modulation.

References

Tlatov, A. G., G. B. Gelfreikh, and V. I. Makarov (2005), Magnetic Field Reversal of the Sun in Polarization of Radioemission at 17GHz, in Large-scale Structures and their Role in Solar Activity, *ed.* K. Sankarasubramanian, Matt Penn, and Alexei Pevtsov, *ASP Conference Series*, *346*, 281.