REPLY

Reply to the comment by Cowley et al. on "Magnetic phase structure of Saturn's 10.7 h oscillations"

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We reply to Cowley et al.'s, (hereafter CPA) comments on *Yates et al.* [2015] (YSD). CPA conclude that the analysis and discussions in YSD are flawed and thus YSD's comments on the postequinox magnetic oscillations determined by *Andrews et al.* [2012] and *Provan et al.* [2013] (henceforth A and P, respectively, or AP) are invalid. We should emphasize that our intention is to build on the results of AP and to examine how one may exploit them further. We are grateful for the attention paid and have found two errors. The use of phase as a coordinate has already been used in work such as *Southwood and Kivelson* [2007]; *Southwood* [2011, 2015] for deducing spatial structure, examining north-south phase differences and nonsinusoidality. The set of northern and southern oscillations as provided by AP is very important. The error in YSD stems from a misunderstanding of the data provided by the Leicester group and is not present in the earlier work cited above. We have reanalyzed the data from the three intervals discussed in YSD (interval A preequinox and intervals B and C postequinox). A correction due to spacecraft local time (LT) was not applied to the magnetic phases determined by AP. Although now corrected, this correction does not result in any significant changes to the results as the orbits in each interval had similar or overlapping trajectories. LT corrections were thus similar in each pass used. The second error detected makes more impact and changes the YSD conclusion. There was a large jump in the phase data provided by P at the beginning of interval C that fed into our interpolation algorithm that affects the phase of the first and last passes in this interval. The revision means the first three passes in interval C are now in phase and consistent with the strong southern dominance in this interval [*Provan et al.,* 2013]. The fourth pass in this interval, however, still exhibits some peculiar behavior after revision and is discussed further below.

During interval B, P determines that the amplitude ratio between the northern and southern oscillations is ~1 suggesting that the magnetic field in the low-latitude region chosen for study might be expected to be governed by the mean phase/period. YSD showed a slight drift of the field oscillations with respect to the mean phase, which suggested that the mean phase determined by AP was incorrect. Figure 1c in CPA shows evidence that in the core region (range $< 12 R_S$) the mean phase governs the magnetic field. CPA present data either side of periapsis and while there does appear to be coherence, there is also evidence of drifting with respect to the mean phase (see peaks near mean phase equals 1 line). CPA then suggest that the reason YSD observe good coherence while using the southern phase is that the spacecraft is within the southern hemisphere and outside the core region. *Provan et al.* [2012] show that outside the core region, the dominance of the magnetic oscillations is inhomogeneous. CPA's alternate interpretation of YSD's interval B observations seems reasonable. CPA also claims that the southern period refinement calculation performed in YSD (section 4.2) is incorrect. This is a heuristic proof of concept calculation and is not intended to represent the true southern period.

As discussed above there was an interpolation error in interval C's analysis, affecting the first and last passes only. The corrected figure is shown in Figure 1. Residual magnetic field components are plotted as a function of southern AP phase. Zero phase is taken as the first integer cycle before periapsis. The colors indicate the pass number of the spacecraft trajectory. Using $dB\phi$ (Figure 1c), this figure improves coherence. However, pass 4 (black line) appears to be in/near anti-phase with passes 2, 3 and 6 (red, green and yellow lines). This is evident within the first few cycles and shown in a different manner in Figure 1d— showing the phase of a current sheet crossing/encounter for $dB\phi$. Current sheet encounters for passes 2, 3, and 6 appear to be between 90° and 180° apart from pass 4. This difference is due to the difference between P's model and determined phases (see CPA Figure1b). CPA and *Provan et al.* [2011] term such deviations from their model phase as "common jitter" due to short-timescale variation in the magnetic periods. We would not dispute that but it serves to emphasize that refined analysis can be useful.
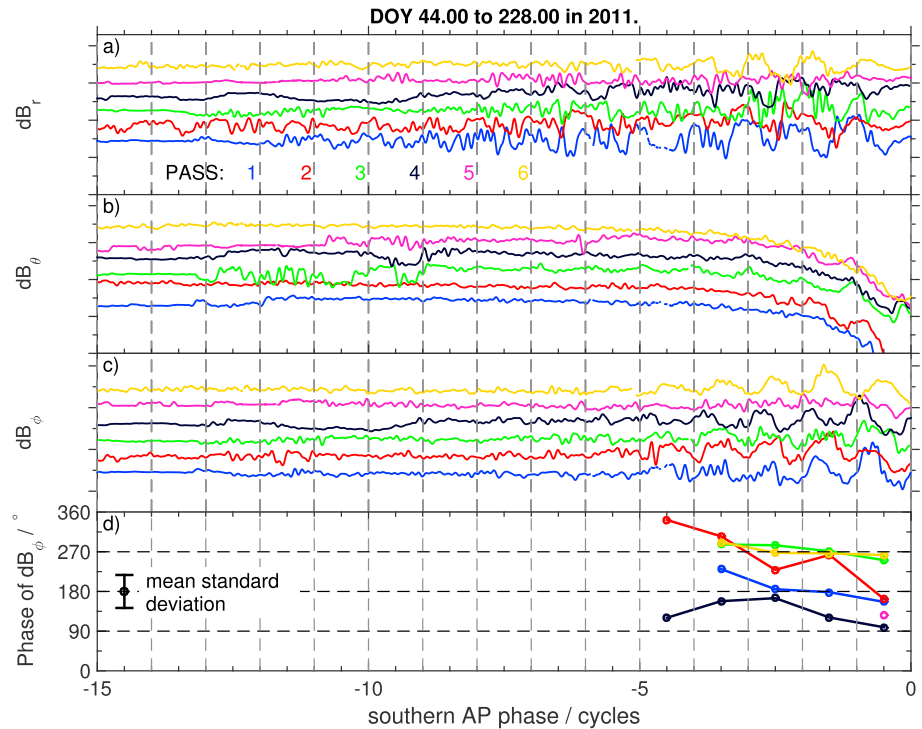
Figure 1. Perturbation magnetic field components as a function of southern AP phase from the 2011 inbound passes (interval C). (a–c) Show the r, θ, and ϕ components of the perturbation magnetic, respectively. (d) The phase of the first current sheet crossing (or approach when the current sheet was not crossed) of the normalized $dB\phi$ component along with the mean standard deviation of the determined phases. Data gaps or encounters of low confidence are omitted from the plot. The arrows highlight the phase jumps to be discussed. The vertical dashed lines indicate a unit cycle. The colors indicate the pass number in the selected time period.

CPA also comment on three points discussed in YSD as possible influences as to why the AP postequinox phases are in need of refinement.

1. YSD state that preequinox SKR phases, obtained using the Radio and Plasma Wave Science instrument, are used as a guide while at the time of AP there was no available postequinox SKR phases. CPA state correctly that the AP work does not use SKR phases as guides but the earlier work does [e.g., *Andrews et al.*, 2008; *Provan et al.*, 2009]. We regret any ambiguity here.
2. CPA is correct that the sinusoidal nature of the magnetic field within the core region has not changed significantly over the Cassini era although there are instances when the field is not sinusoidal.
3. CPA affirms that their data intervals are large enough to account for the beating between the two oscillations. On average this may be true. The minimum difference between the northern and southern periods is ~15 s (using data provided by G. Provan) while CPA state the minimum as ~1.5 min which is approximately the mean difference for interval B. Fifteen seconds gives a half-beat period of ~600 days, considerably larger than the ~100 days given by the mean difference. This large beat interval last for ~25 days and thus can be debated as to whether it has a significant impact on AP's model findings.

CPA corroborates AP's postequinox phase model and magnetic periods with *Provan et al.* [2014]. While we agree that there is agreement (within errors) between their SKR and magnetic periods, one can still see in *Provan et al.* [2014] (Figure 4) that there are noticeable differences between the SKR periodogram periods and those overplotted as the principle peaks of the SKR periods. Further evidence of the difference between magnetic and SKR periods is presented in *Fischer et al.* [2015] (see Figure 11). The most striking difference is the temporal variability of the SKR periods compared to the magnetic periods, which are constant for long intervals (P). Despite the significant differences in periods, *Fischer et al.* [2015] show the SKR and AP phases to be in relatively good agreement. The reanalysis of YSD also indicates a greater coherence with the magnetic field and phase.

We are grateful for CPA's careful scrutiny of our analysis and detection of errors. We are pleased that discrepancies are now substantially fewer. However, there still remain discrepancies with AP with portions of passes being in, or close to, antiphase with each other in interval C. The intention was never to undermine the work of AP but to use their results to refine analysis. Our approach using phase as a coordinate and orbit by orbit comparison to investigate remains, as far as we can see, the only way to separate space and time, something that is particularly significant in regard to where signals are nonsinusoidal. This combined with the temporal variation of the SKR periods compared to those derived by P postequinox still suggests to us that there is room for refinement. The oscillation periods and the source of such phenomena at Saturn still remain unresolved.

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