Planetary period modulations of Saturn’s magnetotail current sheet during northern spring: Observations and modeling

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Abstract

We study Cassini magnetic field observations at Saturn on a sequence of passes through the near-equatorial magnetotail during 2015, focusing on dual modulation of the plasma/current sheet associated with northern and southern planetary period oscillations (PPOs). Previous study of inner magnetosphere PPOs during this northern spring interval showed that the southern system amplitude was generally half that of the northern during the first part of the year to late August, after which the southern amplitude weakened to less than one-fifth that of the northern. We examine four sequential tail passes in the earlier interval, during which prominent PPO-related tail field modulations were observed, with relative (beat) phases of the two PPO systems being near in phase, antiphase, and two opposite near-quadrature conditions. We find that the radial field displayed opposite “sawtooth” asymmetry modulations under opposite near-quadrature conditions, related to previous findings under equinocial conditions with near-equal northern and southern PPO amplitudes, while modulations were near symmetric for in-phase and antiphase conditions, but with larger radial field modulations for in-phase and larger colatitudinal field modulations for antiphase. A simple physical mathematical model of dual modulation is developed, which provides reasonable correspondence with these data using one set of current sheet parameters while varying only the relative PPO phases, thus demonstrating that dual modulation can be discerned and modeled even when the northern and southern amplitudes differ by a factor of ~ 2. No such effects were consistently discerned during the later interval when the amplitude ratio was >5.

1. Introduction

Despite the near axisymmetry of Saturn’s planetary magnetic field (Burton et al., 2010), Cassini observations have shown that modulations near the planetary rotation period of ~10.6 h are ubiquitously present in essentially all magnetospheric parameters (see, e.g., the review by Carbay and Mitchell [2013, and references therein]). In fact, two superposed rotating modulations have been shown generally to be present [Kurth et al., 2008; Gurnett et al., 2009; Andrews et al., 2010b; Provan et al., 2011; Cowley et al., 2016], driven outward into the magnetosphere from the northern and southern polar ionospheres [Jia and Kivelson, 2012; Hunt et al., 2014], whose amplitude and period vary slowly with Saturn’s seasons [Galopeau and Lecacheux, 2000; Gurnett et al., 2011; Andrews et al., 2012; Provan et al., 2013, 2016]. The properties of these “planetary period oscillations” (PPOs) have been monitored near continuously throughout the Cassini mission to date (~2005–2016) using magnetic field oscillation data [Andrews et al., 2008, 2012; Provan et al., 2013, 2014, 2016], while complementary measurements of the period have also been derived from modulations of auroral Saturn kilometric radiation (SKR) emissions [Kurth et al., 2008; Gurnett et al., 2011; Lamy, 2011; Provan et al., 2014, 2016; Ye et al., 2016]. These studies have shown that early in the Cassini mission during late Saturn southern summer, prior to vernal equinox in mid-2009, the southern oscillations with a period of ~10.8 h were dominant over the northern oscillations with a period of ~10.6 h by a factor of ~2.6 by amplitude [Andrews et al., 2012]. The two oscillation periods then converged to a near-common value ~10.7 h with near-equal amplitudes over a 2 year interval centered near equinox (mid-2008 to mid-2010) but did not enduringly reverse sense until mid-2014 during late northern spring (prior to northern solstice in mid-2017) [Andrews et al., 2012; Provan et al., 2014, 2016; Cowley and Provan, 2015, 2016]. At that time the northern period increased rapidly to reach ~10.8 h by the middle and end of 2015, while the southern period remained near ~10.7 h over this interval [Provan et al., 2016]. The northern oscillation was also found to be dominant over the southern by a factor of ~2.3 to mid-2015, increasing to a factor greater than ~5 to the end of that year.

The first indication that the PPOs significantly affect the planetary magnetodisk and adjacent plasma/current sheet in Saturn’s nightside tail, the topic of the present paper, was obtained by Carberry et al. [2008], who
found using energetic neutral atom images obtained in late 2004 that the near-equatorial plasma layers oscillated north-south at the period of the then dominant southern PPO. Correspondingly, Jackman et al. (2009) showed that PPO-related modulations in the magnetic field and plasma populations indicative of north-south oscillations of the plasma/current sheet were observed throughout the first season of Cassini tail observations during 2006. Morooka et al. (2009) also analyzed plasma density data obtained during mid-2004 to mid-2007 by the Cassini Langmuir probe and showed that the equatorial plasma layer not only oscillated north-south near the southern PPO period but was also modulated in thickness, such that the sheet was thicker and more dense when displaced to the south and thinner and less dense when displaced to the north. The north-south oscillations were subsequently modeled by Arridge et al. (2011) using the southern PPO phases derived from magnetic data by Andrews et al. (2008), who found that the motion could be described as an oscillatory tilting of the plasma/current sheet at the southern period through ±12°, hinging at a radial distance of 12 R₉. While this model accounted well for observations obtained near the planetary equatorial plane, which principally explored conditions south of the current sheet center due to the seasonal northward displacement of the sheet during southern summer (Arridge et al., 2008), it was found not to similarly organize data from subsequent tilted orbits that also explored the region north of the current sheet center.

With the subsequent realization that two PPO modulations are simultaneously present, one driven from the northern ionosphere and the other from the southern (Gurnett et al., 2009; Andrews et al., 2010b), the 2006 tail data set was reexamined by Provan et al. (2012), who showed that while the oscillations observed in the southern tail are indeed associated with the southern PPO system, those in the northern tail are instead associated with the northern PPO system, thus explaining the model breakdown found by Arridge et al. (2011). The central current sheet region, however, was found to be dual modulated by both oscillations, though with the northern being the stronger during the prequinox interval investigated. With dual modulation, however, the form of the overall oscillations must depend on the relative phase of the two systems (the PPO “beat phase”), with Provan et al. (2012) showing that north-south oscillations are principally involved when the two systems are in phase, while significant thickness modulations are superposed when they are in antiphase (the precise meaning of the PPO phases will be discussed in section 2). Specifically, under the antiphase condition the current sheet was found to be thicker when displaced to the south in the dominant southern PPO cycle and thinner when displaced to the north, in agreement with the results of Morooka et al. (2009).

Dual modulation effects are expected to become even more prominent during equinoctial conditions when the two PPO amplitudes become near equal (Andrews et al., 2012). Szego et al. (2013) modeled tail field and plasma data obtained during the transequinoctial interval 2009–2010 using a modification of the Arridge et al. (2011) model in which northern and southern oscillations are superposed taking account of their relative phase. They found good agreement with observed displacement effects with a north/south displacement amplitude ratio \( k = 0.95 \). Most recently, however, Thomsen et al. (2017) have examined the Cassini field data from the 2010 tail season in more detail and found the presence of new PPO-related effects. Specifically, during some tail passes the periodic transitions from the north to the south of the current sheet center take place more rapidly than the subsequent transitions from the south to the north, giving rise to a “sawtooth” waveform in the principal radial magnetic field component. On other passes, however, the sense of the asymmetry is reversed while being absent on yet others. Thomsen et al. (2017) showed that these behaviors were related to the beat phase of the two PPO systems derived previously from inner magnetosphere magnetic data by Provan et al. (2013), with opposite sawtooth forms being related to the two near-quadrature conditions (north leading south or vice versa), while their absence occurred during near-in-phase or near-antiphase conditions. Cowley et al. (2017) showed that this set of behaviors can be accounted for by a simple mathematical model in which displacement and thickness modulations are related to the polarization of the magnetic perturbations produced by the two PPO systems, as discussed in section 2. Such beat phase effects will clearly be most prominent when the amplitudes of the two systems are near equal, as during the transequinoctial interval examined by Thomsen et al. (2017). They are expected to become less marked as the north/south ratio deviates from unity, the modulations then relating more to the dominant oscillation, i.e., the southern oscillation in late southern summer prequinox and the northern oscillation in late northern spring postequinox. On the basis of their modeling study, Cowley et al. (2017) suggested that a limiting amplitude ratio for clearly discernable beat phase effects is likely a factor of \( \approx 2 \) between the dominant and secondary oscillations. In this context Thomsen et al. (2017) also examined the earlier interval of Cassini tail data obtained during southern summer in 2006 when the north/south amplitude ratio was \( k \approx 1/2.6 \) and found that related
asymmetries were hard to discern. A third and final interval of near-equatorial Cassini tail passes also took place during 2015 after period reversal [see Cowley et al., 2017, Figure 1], for which the north/south amplitude ratio was \( k \approx 2.3 \) during the first part of the year to late August, increasing after that to greater than \(~5\), as indicated above. Here we examine these data to determine whether beat phase asymmetry effects can be discerned under such near-limiting conditions and show that they are indeed present during the earlier interval of 2015, though being less distinct than in the transequinoctial 2010 data, but are not discerned in the later interval. Consideration of these data is supported by physical modeling calculations using an augmented version of the mathematical model introduced by Cowley et al. [2017].

2. Theoretical Basis and Mathematical Model

2.1. Physical Picture

The theoretical basis for understanding the PPO-related modulations of the tail plasma/current sheet is shown in Figure 1 taken from Cowley et al. [2017], based on the prior discussions of Andrews et al. [2010a] and Provan et al. [2012]. In Figures 1a and 1c we show the field perturbations associated with the two PPO systems drawn in their principal meridian planes, where the blue arrowed lines in Figure 1a correspond to the northern system and the red arrowed lines in Figure 1c to the southern system. The black arrowed lines correspond to the background magnetospheric magnetic field, to a first approximation axisymmetric about the vertical spin/magnetic axis. In each case the perturbations form a quasi-uniform field in the equatorial magnetosphere which closes via a transverse quasi-dipolar field over the corresponding pole. Position with respect to these systems is defined by an azimuthal phase angle \( \Psi_{N,S} \) shown by the blue (northern, N) and red (southern, S) symbols in the figures, defined for both systems such that the quasi-uniform field points radially outward where \( \Psi_{N,S} = 0^\circ \) (to the right in both diagrams), and radially inward where \( \Psi_{N,S} = 180^\circ \) (to the left in both diagrams). Phase \( \Psi_{N,S} \) then increases clockwise around the planet as viewed from the north, such that these values increase steadily with time at a fixed position as the systems rotate near the planetary rotation period.

The effect of these fields on the equatorial current sheet is illustrated in Figures 1b and 1d, which show the effect of the northern and southern PPO systems, respectively. For economy of drawing we show the effects

![Figure 1. Sketches of the perturbation fields associated with (a) the northern and (c) the southern PPO systems, and (b and d) the plasma/current sheet modulation effects to which they give rise. Figures 1a and 1c show the perturbation fields (arrowed blue and red lines) in their prime \( \Psi_{N,S} = 0^\circ - 180^\circ \) meridians, together with the background magnetospheric field (arrowed black lines), near symmetric about the vertical planetary spin/magnetic axis. Figures 1b and 1d show the corresponding north-south displacements and modulations in thickness of the magnetodisk and tail current sheet contained in the region between the pairs of dashed lines [from Cowley et al., 2017].](image-url)
for \( \Psi_{N,S}=0^\circ \) and \( \Psi_{N,S}=180^\circ \) on opposite sides of each diagram as indicated, though here we will be concerned principally with the current sheet in the near-midnight tail. It can first be seen that when \( \Psi_{N,S}=0^\circ \) the positive radial perturbation field adds to the magnetospheric radial field north of the current sheet center and subtracts from it south of the current sheet center, and vice versa for the negative radial field for \( \Psi_{N,S}=180^\circ \). Bearing in mind that on the timescale of these oscillations quasi-static pressure balance must be maintained across the current sheet, the implication is that the current sheet is displaced to the south for both systems when \( \Psi_{N,S}=0^\circ \) and to the north when \( \Psi_{N,S}=180^\circ \), as shown in Figures 1b and 1d. Second, we see that when the colatitudinal perturbation field is positive, directed southward in the equatorial region in the same sense as the planetary field, as it is for the northern system when \( \Psi_{N}=180^\circ \) and for the southern system when \( \Psi_{S}=0^\circ \), it increases the magnetic flux through the center of the current sheet, thereby widening the sheet. When the colatitudinal perturbation field is negative, however, directed northward in the equatorial region opposite to the planetary field, as it is for the northern system when \( \Psi_{N}=0^\circ \) and for the southern system when \( \Psi_{S}=180^\circ \), it reduces the magnetic flux through the center of the current sheet, thereby thinning the current sheet. These effects are also sketched in Figures 1b and 1d, where we see that due to the opposite relative phasing between the radial and colatitudinal field perturbations in the two systems, antiphase for the northern system and in phase for the southern, for the northern system the current sheet is thickened when displaced to the north and thinned when displaced to the south, while for the southern system it is thinned when displaced to the north and thickened when displaced to the south. The latter expectations are in agreement with the observations of Morooka et al. [2009] and Provan et al. [2012] outlined in section 1, under the southern-dominant conditions examined in those studies.

More generally, however, we must consider the effects of both PPO systems combined. Assuming that the effects are approximately additive, it can be seen that when the two systems are in phase, i.e., \( \Psi_{N} = \Psi_{S} \) modulo 360°, the north-south oscillations will reinforce each other while the thickness modulations will tend to cancel, while when the two systems are in antiphase, i.e., \( \Psi_{N} = \Psi_{S} + 180^\circ \) modulo 360°, the north-south oscillations will tend to cancel while the thickness modulations will reinforce each other. These expectations are clearly in accord with the observations of Szego et al. [2013] with regard to the amplitude of the northsouth oscillations and the results of Provan et al. [2012] with regard to the relative role of thickness modulations. We further note that related modulation effects have also been reported in the computational modeling results of Jia and Kivelson [2012]. Clearly, the largest such effects should be found under equinoctial conditions when the two systems have near-equal amplitudes, leading, e.g., to near doubling of the northsouth oscillation amplitude and cancellation of the thickness modulations under in-phase conditions, and vice versa for antiphase. However, even when the amplitudes of the two systems differ by a factor of \(~2\), as during the initial part of the 2015 tail season, the maximum/minimum amplitude ratio is expected to be approximately \((1 + 0.5)/(1 − 0.5) = 3\), which may lead to discernable effects over the beat phase cycle of the two oscillations.

In addition to the reinforcement and cancellation effects that occur near in-phase and antiphase conditions as just discussed, it was also shown by Cowley et al. [2017] on the basis of the physical picture in Figure 1 that when the two systems are near to quadrature the oscillating current sheet is thicker when moving through its equilibrium position in one direction than in the other, leading to sawtooth modulations in the near-equatorial radial field with opposite senses for opposite senses of quadrature (north leads south or vice versa), as discussed in section 2.2. These effects, together with their disappearance for near-in-phase or near-antiphase conditions, was found to provide a reasonable account of the equinoctial tail data studied by Thomsen et al. [2017]. Here we will consider the same picture in relation to the 2015 tail data, for which the north/south ratio was \( k \approx 2 \) during the first part of the year to late August, then increasing further to \( >5 \) [Provan et al., 2016].

### 2.2. Mathematical Model for the Radial Field Component

In the mathematical model proposed by Cowley et al. [2017] the spatial variation of the principal radial component of the tail field was represented, e.g., as in Arridge et al. [2011], as a hyperbolic tangent function of north-south position \( z \)

\[
\frac{B_z}{B_{zo}} = \tanh \left[ \frac{z - z^*}{D^*} \right].
\]
where $D^*$ is a measure of the half width of the current sheet and noting that $\tanh(\pm \infty) = \pm 1$, $B_{ro}$ is the lobe field strength at large distance from the center of the current sheet at $z = z^*$. In conformity with the discussion in section 2.1, the modulation effects on the position and thickness of the sheet are represented by

$$z^*(\Psi_N, \Psi_S) = -(z_N \cos \Psi_N + z_S \cos \Psi_S),$$

(2)

related to the radial perturbation fields of the two PPO systems which vary approximately as $\cos \Psi_{N,S}$ and

$$D^*(\Psi_N, \Psi_S) = D - (D_N \cos \Psi_N - D_S \cos \Psi_S),$$

(3)

related to the colatitudinal perturbation fields of the two PPO systems which vary approximately as $-\cos \Psi_N$ for the northern system and $+ \cos \Psi_S$ for the southern (see Figure 1). We note in equation (3) that the thickness modulation amplitudes must satisfy $(D_N + D_S) < D$, such that $D^*$ remains positive throughout the dual oscillation beat cycle. We also assume that the modulation amplitudes $z_{N,S}$ and $D_{N,S}$ are simply proportional to the amplitudes of the perturbation fields of the two systems. Thus, if the north/south amplitude ratio is $k$ (as determined, e.g., through examination of the combined oscillations within the quasi-dipolar “core” region in the inner magnetosphere [e.g., Andrews et al., 2012; Provan et al., 2013, 2016]), we assume that at least approximately

$$\left(\frac{z_N}{z_S}\right) = \left(\frac{D_N}{D_S}\right) = k,$$

(4)

as must clearly be the case when $k \approx 1$, then giving near-equal responses to near-equal perturbation fields. While the above model was found by Cowley et al. [2017] to be adequate to demonstrate the beat phase effects found in the equinoctial radial field data by Thomsen et al. [2017], no close comparisons were made in those papers. Here we do compare the model with data from specific tail passes during the 2015 tail season and find that a more realistic representation is obtained using a radial field profile in which the main current layer of relatively narrow (few planetary radii) half width is embedded within a wider modulated region of modest field depression compared with the lobes (see further discussion below and in section 3.1). Here we thus employ a profile given by the modified form

$$\frac{B_z}{B_{ro}} = a\tanh\left(\frac{z - z^*}{D^*}\right) + b\tanh\left(\frac{z - z^*}{cD^*}\right),$$

(5)

where we find a reasonable representation using $a = 0.7$, $b = 0.3$, and $c = 5$. We note that while these quantities may be regarded as indicative, we do not place great emphasis on their detailed values. The solid line in Figure 2 shows the modified profile plotted versus $(z/D^*)$ using $z^* = 0$, while the dashed line shows the basic profile given by equation (1). The two forms are seen to be very similar, except for a slower approach to the limiting normalized values $\pm 1$ at $z = \pm \infty$ for $(|z|/D^*) > 2$.

We now exemplify the results of the simple mathematical model given by equations (2)–(5) using parameters germane to subsequent comparisons with the 2015 tail data. Specifically, as in Cowley et al. [2017] we employ an undisturbed current sheet half width $D = 2.5$ $R_S$ in equation (3), based on the modeling results of Arridge et al. [2011] who found half widths between 1.5 and $6 R_S$ with an average of $\sim 2.5 R_S$ ($R_S$ is Saturn’s 1 bar equatorial radius equal to 60,268 km.) In section 3 we find that this value also provides a reasonable description of the 2015 tail data examined here, though with indications sometimes of smaller half widths (section 3.1), as reported previously by Kellett et al. [2009] and Sergis et al. [2011]. Examination of the plasma sheet particle populations has also shown that while thermal ions are concentrated within the central current sheet, hot ions and electrons may extend with diminishing density $\sim 5–10$ $R_S$ on either side of the center [Sergis et al., 2011; Nemeth et al., 2011; Szego et al., 2011]. Correspondingly, given undisturbed half width $D = 2.5$ $R_S$ as indicated above, the undisturbed half width of the wider secondary plasma/current layer in equation (5), equal to $SD$, is $12.5 R_S$. A northern thickness modulation amplitude $D_N = 1 R_S$ is also found to provide reasonable results, such that from equation (4) $D_S = 1/k R_S$ (applicable to the northern dominant regime $k \geq 1$ examined here). We also employ a north-south oscillation amplitude for the dominant northern oscillation of $z_N = 2 R_S$.
in equation (2), reduced compared with the 4 $R_S$ value employed by Cowley et al. [2017], such that again from equation (4) $z_S = 2/k R_S$. The smaller value is appropriate to the 2015 tail data examined here due to the seasonal current sheet displacement mentioned in section 1 which typically limits observations of prominent tail field oscillations on near-equatorial orbits to radial distances less than $\sim 25 R_S$ (see section 3 below). Oscillations were often observed to these and larger distances in the equinoctial data examined by Thomsen et al. [2017] for which the seasonal current sheet displacement was near zero. Noting that Arridge et al. [2011] modeled the oscillations as an angular displacement of the sheet center through $\pm 12^\circ$ hinging at $12 R_S$ as indicated in section 1, a dominant system amplitude of $\sim 2 R_S$ is considered appropriate at smaller down tail distances $\sim 20 R_S$ representative of the 2015 data, while the somewhat larger amplitude of $4 R_S$ employed by Cowley et al. [2017] is appropriate at larger down tail distances $\sim 30 R_S$ representative of the equinoctial data.

Results are shown in Figure 3, where parameters are plotted versus the phase of the dominant northern oscillation $\Psi_N$ employed as a time proxy, over two cycles of oscillation. Each column of plots shows results for a given value of the phase difference between the two systems, the beat phase, defined as

$$\Delta \Phi = \Psi_N - \Psi_S,$$  \hfill (6)

taken to be constant in each plot (for near-equal oscillation periods). We note that in principle we could employ northern $\Psi_N$ and southern $\Psi_S$ phases varying with time in accordance with individual northern and southern oscillation periods in all of the model equations. However, as will be seen in section 3 below, because the two periods are in practice so similar, differing by only of order $\sim 1\%$, the beat phase does not change greatly in value over the few-day (several PPO cycle) intervals considered in later sections. Thus, taking a fixed beat phase (with consequent equal periods) for purposes of clear illustration of beat phase-related effects represents a significant and appropriate modeling simplification. Figures 3a–3d then correspond to in-phase conditions $\Delta \Phi = 0^\circ$ modulo 360°, Figures 3e–3h to antiphase $\Delta \Phi = 180^\circ$, Figures 3i–3l to north leads south near-quadrature $\Delta \Phi = 120^\circ$, and Figures 3m–3p to south leads north near-quadrature $\Delta \Phi = 240^\circ$ (equivalent to $\Delta \Phi = -120^\circ$ modulo 360°). The values $\Delta \Phi = \pm 120^\circ$ are employed rather than exact quadrature, $\Delta \Phi = \pm 90^\circ$, since analysis shows that these give maximum sawtooth effects for amplitude ratio $k = 2$ [see Cowley et al., 2017, equation (11b)], applicable to the 2015 tail data.

The top plot in each column (Figure 3a et seq.) shows the two rastering PPO phases modulo 360°, $\Psi_N$ by the same blue line in each plot, and $\Psi_S = \Psi_N - \Delta \Phi$ by the red line, while the beat phase $\Delta \Phi$ is shown by the horizontal black dashed line. The second and subsequent plots in each column show the modulated normalized radial field $B_r/B_{ro}$ given by equations (2)–(5) for north/south amplitude ratio $k = 1$ corresponding to

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{brbro.png}
\caption{Plot of the model profiles of the normalized radial component of the magnetic field given by equations (5) (solid line) and (1) (dashed line).}
\end{figure}
near-equinoctial conditions (Figure 3b et seq.), \( k = 2 \) corresponding to conditions during the earlier part of 2015 (Figure 3c et seq.), and \( k = 5 \) corresponding to conditions during the later part of 2015 (Figure 3d et seq.). The black line in each plot shows the normalized radial field variation at a fixed position at the center of the unmodulated sheet \( z = 0 \), while the green and purple lines show the variation at \( z = 2.5 R_S \) and \( z = 2.5 R_S / k \) respectively. The undisturbed half width of the current sheet is \( D = 2.5 R_S \) with northern and southern modulation amplitudes of \( D_N = 1 R_S \) and \( D_S = 1 / k R_S \) (equations (3) and (4)), respectively, while the northern and southern north-south oscillation amplitudes are \( z_N = 2 R_S \) and \( z_S = 2 / k R_S \) (equations (2) and (4)), respectively.

We first consider Figures 3b, 3f, 3j, and 3n, which shows results for the special (near-equinoctial) case of equal northern and southern amplitudes, \( k = 1 \). When the two systems are in phase, as shown in Figure 3b, the equal north-south oscillations reinforce each other while the thickness modulations cancel, such that the field variations are due only to north-south oscillations of the current sheet with a combined amplitude of \( 4 R_S \) with maximum southward displacement at \( \Psi_N = \Psi_S = 0^\circ \) modulo 360\(^\circ \) and maximum northward displacement at \( \Psi_N = \Psi_S = 180^\circ \) modulo 360\(^\circ \) (equation (2)). While such an oscillation amplitude is comparable with the full \( 5 R_S \) width of the narrower primary current sheet in equation (5), it is modest compared with the full \( 25 R_S \) width of the wider secondary current sheet. The presence of the wider secondary sheet thus results in a slower approach of the normalized radial field toward the limiting values of \( \pm 1 \) near the extrema of the oscillation, resulting in a more “rounded” rather than “flat-topped” oscillating radial field profile (compare with Figures 7–9 of Cowley et al. [2017] where the secondary term was not
included). It is this feature, found generally to be present in the 2015 tail data (see section 3 below), that motivates inclusion of the secondary term in equation (5). When the two systems are in antiphase, however, as shown in Figure 3f, the equal north-south oscillations cancel while the thickness modulations reinforce, such that the field variations are due only to thickness modulations. The minimum half-thickness $D^* = 0.5 \ R_S$ occurs at $\Psi_N = 0^\circ$ modulo 360° where the field strengths maximize on either side of the current sheet, while the maximum half-thickness $D^* = 4.5 \ R_S$ occurs at $\Psi_N = 180^\circ$ where the field strengths minimize. The field remains zero exactly at the center of the current sheet in this case, in the absence of north-south oscillations.

For the two near-quadrature cases shown in Figures 3j and 3n, however, north-south oscillations and thickness modulations are both present, with a relative phase that results in opposite sawtooth waveforms in the radial field. For $\Delta \Phi = 120^\circ$ shown in Figure 3j the sheet is thicker when moving from south to north around $\Psi_N = 180^\circ$ modulo 360° than when moving from north-south around $\Psi_N = 0^\circ$, thus giving a slower transition in the former case than in the latter. The opposite asymmetry occurs for $\Delta \Phi = 240^\circ$ in Figure 3n, leading to a sawtooth waveform of the opposite sense. The physical origin of the sawtooth waveforms lies in the opposite polarization of the radial and colatitudinal field perturbations in the two systems as illustrated in Figure 4, where we show the pattern of the north-south oscillations and thickness modulations for both systems in a view looking down on the equatorial plane from the north, together with the model sawtooth waveforms in the radial field. For $\Delta \Phi = 0^\circ$ shown in Figure 3k the sheet is thicker when moving from north to south around $\Psi_N = 0^\circ$ modulo 360° than when moving from north-south around $\Psi_N = 180^\circ$, thus giving a slower transition in the former case than in the latter. The opposite asymmetry occurs for $\Delta \Phi = 90^\circ$ in Figure 3l, leading to a sawtooth waveform of the opposite sense. The physical origin of the sawtooth waveforms lies in the opposite polarization of the radial and colatitudinal field perturbations in the two systems as illustrated in Figure 4, where we show the pattern of the north-south oscillations and thickness modulations for both systems in a view looking down on the equatorial plane from the north, together with the model sawtooth waveforms in the radial field.

For a fixed equatorial observer at point A in Figure 4a, $B_0$ increases from negative to positive values as the sheet center moves from north-south with the current sheet being thin at that time, giving rise to a rapid transition, while for a fixed observer at point B, $B_0$ decreases from positive to negative values as the sheet center moves from south to north with the current sheet being thick at that time, giving rise to a slow transition. The configuration in Figure 4a thus gives rise to a sawtooth $B_0$ profile with a fast rise and a slow fall in $B_0$, as in Figure 4b, where we show the model profile at $z = 0$ for $\Delta \Phi = +90^\circ$ and $k = 1$ with the other model parameters as in Figure 3. For a fixed equatorial observer at point A in Figure 4c, however, $B_0$ similarly increases from negative to positive values but the current sheet is now thick at that time, giving rise to a slow transition, while at point B, $B_0$ similarly decreases from positive to negative values with the current sheet being thin at that time, giving rise to a fast transition. The configuration in Figure 4c thus gives rise to a sawtooth $B_0$ profile with a slow rise and a fast fall in $B_0$, as in Figure 4d, where we similarly show the model profile at $z = 0$ for $\Delta \Phi = -90^\circ$ and $k = 1$.

Returning to Figure 3, Figures 3c, 3g, 3k, and 3o show results for north/south amplitude ratio $k = 2$, germane to the data studied here in the earlier interval of 2015, in which case north-south oscillations and thickness modulations occur throughout. The north-south oscillations have a maximum amplitude of 3 $R_S$ when the two PPO systems are in phase in Figure 3c and a minimum amplitude of 1 $R_S$ when they are in antiphase in Figure 3g, while the thickness modulations are minimum with $D^*$ varying between 2 and 3 $R_S$ when the two systems are in phase and maximum with $D^*$ varying between 1 and 4 $R_S$ when in antiphase. The field variations for in-phase conditions are still dominated by the north-south oscillations in this case, while the combined effects of both north-south oscillations and thickness modulations are evident for antiphase conditions, the two effects reinforcing each other north of the sheet center and part canceling south of the
center. For the two near-quadrature cases in Figures 3k and 3o, sawtooth waveforms with opposite senses are still evident, though of less extreme form than for $k=1$.

Figures 3d, 3h, 3l, and 3p similarly show results for amplitude ratio $k=5$, germane to the later interval of 2015, such that the northern system dominates throughout. For the northern system alone the model north-south amplitude is $2.4 R_S$ as indicated above, while the half thickness is modulated between $1.5$ and $3.5 R_S$. With $k=5$, the oscillation amplitude is increased to $2.4 R_S$ for in-phase conditions and reduced to $1.6 R_S$ for antiphase, while the half thickness modulations are reduced to between $1.7$ and $2.3 R_S$ for in phase and increased to between $1.3$ and $3.7 R_S$ for antiphase. While clear northern-dominated oscillations should still be present, particularly north of the current sheet center, these beat phase variations are sufficient to produce only minor differences in the radial field profiles in each case, with only weak sawtooth asymmetries being present in Figures 3l and 3p.

2.3. Simple Normalized Models for the Colatitudinal and Azimuthal Field Components

In addition to the model for the normalized radial field discussed in section 2.2, based on that discussed previously by Cowley et al. [2017], here we now introduce some normalized forms for the PPO-related variations.
of the colatitudinal and azimuthal components, so that in particular the phasing of their modulations can be simply examined relative to those of the radial field. The variation of the colatitudinal component, the basis of the sheet thickness modulations discussed in section 2.1, is taken simply to be given by

$$\frac{B_\theta}{B_{\theta0}} = 1 - \alpha_\theta \left[ \cos \Psi_N - \frac{1}{k} \cos \Psi_S \right].$$ \hspace{1cm} (7)

where the initial value of unity represents the normalized undisturbed magnetospheric field on which the PPO-related modulations are superposed, antiphase with $B_r$ for the northern system and in phase for the southern system (Figure 1). We also arbitrarily take constant $\alpha_\theta = 1/3$, so that (for $k \geq 1$) the value of the normalized field does not become negative, unphysically suggestive of pinched-off tail field lines. We emphasize that equation (7) is used only to graphically check the relative phasing between the component modulations.

The normalized azimuthal field is taken to be the sum of two components. The first is the "sweepback" field due to plasma subcorotation that causes field lines to be bent out of meridian planes into a "lagging" configuration. If the azimuthal sweepback angle to the radial direction is $\alpha$, approximately constant across the width of the plasma/current sheet at a certain radial distance, then the azimuthal sweepback field is related to the radial field by $B_\phi = -B_r \tan \alpha$. In normalized form this field can then be represented as

$$\frac{B_\phi}{B_{\phi0}} = -\left( \frac{B_r}{B_{r0}} \right).$$ \hspace{1cm} (8a)

where $B_{\phi0} = B_{r0} \tan \alpha$ and $B_r/B_{r0}$ is given by equation (5). The second component is the direct PPO-related azimuthal perturbation field associated with the rotating quasi-uniform or quasi-dipolar field (Figure 1), varying as $+ \sin \Psi_{N,S}$ for the quasi-uniform field in the inner region, and as $- \sin \Psi_{N,S}$ for the quasi-dipolar field in the outer region. This oscillatory field is thus represented as

$$\frac{B_\phi}{B_{\phi0}} = \alpha_\phi \left[ \sin \Psi_N + \frac{1}{k} \sin \Psi_S \right].$$ \hspace{1cm} (8b)

where empirically determined $\alpha_\phi$ may take either positive or negative values depending on whether the PPO field refers to the quasi-uniform or quasi-dipolar perturbations, respectively. The total normalized azimuthal field is thus taken to be given by

$$\frac{B_\phi}{B_{\phi0}} = \left( \frac{B_\phi}{B_{\phi0}} \right)_S + \left( \frac{B_\phi}{B_{\phi0}} \right)_O = -\left( \frac{B_r}{B_{r0}} \right) + \alpha_\phi \left[ \sin \Psi_N + \frac{1}{k} \sin \Psi_S \right].$$ \hspace{1cm} (8c)

We note that the results of Andrews et al. [2010a, Figure 4a] indicate that the switch in azimuthal field behavior between quasi-uniform and quasi-dipolar takes place around ~20 $R_S$ in the equatorial midnight sector, thus lying within the domain of the tail field data examined here.

## 3. Data Set and Examples

The principal data set examined in this study consists of the magnetic field measurements obtained on the outbound passes of Cassini Revs 211 to 230, spanning January 2015 to January 2016, for which the orbit was located close to Saturn’s equatorial plane with apoapsis on the nightside. During the northern spring conditions prevailing, the center of the current sheet was displaced south of the equatorial plane, increasingly with increasing radial distance, such that observations of the current sheet were limited to the region north of the center ($B_r$ positive), with good contact with the sheet generally being limited to radial distances within ~25 $R_S$ as noted above. Both before and after this interval the orbit was increasingly tilted out of the equatorial plane with apoapsis in the northern hemisphere, thus further restricting, if not entirely eliminating, contact with the modulated current sheet. Primarily considering, then, the above near-equatorial orbits, we note that the results of Provan et al. [2016, Figure 6a] obtained from analysis of the PPO perturbation fields observed...
within the quasi-dipolar core region of the magnetosphere (dipole \( L \leq 12 \)) show that the value of the north/south amplitude ratio was \( k \approx 2 \) during Revs 211–220 spanning mid-January to late August 2015 (though with indications of a short-term return to southern dominance around Rev 215), increasing to \( k > 5 \) for later Revs spanning early September 2015 to mid-January 2016 such that the phase modulation effect of the southern oscillation could no longer be discerned within the core region. Consideration of Figure 3 then shows that while beat phase effects might be discernable in the earlier current sheet data, they may not be evident in the later data for Rev 221 and beyond. Examination of the earlier data reveals that prominent PPO-related tail field modulations were observed on the outbound passes of four sequential orbits, Revs 217–220, with a near-optimal set of Provan et al. [2016] beat phase values that allow examination of near in phase, near antiphase, and opposite near-quadrature conditions. It is therefore on these data that we concentrate in sections 3.1–3.4. We then more briefly address the tail field observations during both earlier (Revs 211–216) and later (Revs 221–230) tail passes in sections 3.5 and 3.6, respectively.

### 3.1. Rev 219

We begin by examining the data for Rev 219 for which the two PPO oscillations are approximately in phase, forming a useful baseline for consideration of the data from the other Revs. Figure 5 first shows the orbit of Rev 219 located close to Saturn’s X-Y equatorial plane, for which the corresponding Z axis is aligned with Saturn’s spin/magnetic axis, such that the X-Z plane contains the Sun (to the right in the figure). The dotted lines show magnetopause and bow shock locations for a typical solar wind dynamic pressure of 0.03 nPa according to the models of Kanani et al. [2010] and Masters et al. [2008], respectively, while the blue dashed circle at a radial distance of 12 \( R_S \) indicates the approximate equatorial outer boundary of the core region of the magnetosphere dominated by the planetary field. The black circles on the trajectory indicate start-of-day markers with DOY 2015 being indicated every 2 days, while the red segment shows the 4 day interval starting at periapsis for which magnetic data are shown in Figure 6.

The data from this segment of Rev 219 are shown in Figure 6. Figure 6a shows the phases of the northern (\( \Psi_N \), blue) and southern (\( \Psi_S \), red) PPO oscillations modulo 360° obtained from the phase model of Provan et al. [2016], while the dashed line shows the beat phase \( \Delta \Psi \) (equation (6)), similar to Figures 3a, 3e, 3i, and 3m. The core region magnetic field analysis of Provan et al. [2016] yields a model of the azimuth of...
the $\Psi_{N,S} = 0^\circ$ meridians of the two PPO systems relative to the noon meridian versus time, $\Phi_{N,S}(t)$, increasing positive in the direction of planetary rotation, from which the $\Psi_{N,S}(t)$ phases at the spacecraft within the core region are derived from

$$\Psi_{NS}(t) = \Phi_{NS}(t) - \phi(t),$$  \hspace{1cm} (9a)

where $\phi(t)$ is the azimuth of the spacecraft relative to the noon meridian (equivalent to LT). Outside of the
core region (radial distances $r$ greater than $12 \, R_S$) account must also be taken of the phase delay with radial distance, such that

$$\Psi_{N,S}(t) = \Phi_{N,S}(t) - \varphi(t) - G[r(t) - 12 \, R_S],$$

(9b)

where radial phase gradient $G$ is taken to be $3^\circ \, R_S^{-1}$ following the results of Arridge et al. [2011] and Provan et al. [2012]. Of course, neither the azimuth of the spacecraft nor the radial phase delay enter into the determination of the beat phase, though we are also interested here in the relation between the observed tail field oscillations and the absolute values of the PPO phases $\Psi_{N,S}(t)$, as modeled for the radial field component in Figure 3. We note that over the interval of the four Revs studied in detail here the PPO periods were near-constant at $\sim 10.78$ h for the northern system and $\sim 10.70$ h for the southern, such that the beat period was $\sim 60$ days [Provan et al., 2016]. Thus, only small changes in beat phase $\sim 20^\circ$ occur across the 4 day intervals shown in this and subsequent data figures, while large $\sim 120^\circ$ changes occur over the $\sim 20$ day orbit period intervals from Rev to Rev. Note that since the northern period is longer than the southern during this interval, the beat phase defined by equation (6) decreases in value with time.

Figures 6b–6d show the spherical polar components of the magnetic field observed on Rev 219, referenced to the northern planetary spin/magnetic axis, where the scales in each plot are the same corresponding to a total change in field of 15 nT, while the specific ranges shown have been tailored to each component. Figure 6e shows the north-south position $Z$ of the spacecraft (solid line), very close to the planetary equatorial plane (dotted line), together with the expected position of the center of the current sheet calculated using the empirical model derived by Arridge et al. [2008] (dashed line). Here we have employed a model hinging distance of $25 \, R_S$, in agreement with energetic neutral atom image modeling results derived specifically for 2015 by Carberry and Mitchell [2016]. It is seen that the displacement between the spacecraft and the sheet center during the interval of observed current sheet oscillations (colored stripes, see below) is expected to be typically $\sim 1–3 \, R_S$ beyond which the oscillations become indistinct. Spacecraft data at the bottom of the figure show the time in DOY 2015, the radial distance in $R_S$, the latitude in degrees, and the LT in decimal hours.

Examining the field component data in Figure 6, the transition between the postperiapsis core region and the oscillating plasma/current sheet is first evident midway through DOY 209 at a radial distance of $\sim 15 \, R_S$. Inside the core region, where the equatorial field is dominated by the planetary colatitudinal $B_\theta$ component (Figure 6c), the radial $B_r$ (Figure 6b) and azimuthal $B_\phi$ (Figure 6d) components primarily display the quasi-sinusoidal oscillations of the rotating quasi-uniform PPO perturbation field (northern and southern systems combined), as illustrated in Figures 1a and 1c. Peaks in $B_\phi$ occur when $\Psi_N \approx \Psi_S \approx 0^\circ$ modulo $360^\circ$ in Figure 6a as expected, with peaks in $B_\theta$ occurring one quarter cycle later. Outside this region we note the periodic but highly nonsinusoidal fields associated with the oscillating tail plasma/current sheet of primary focus here. In this region the $B_r$ component exhibits relatively broad positive maxima around times when $\Psi_N \approx \Psi_S \approx 0^\circ$ modulo $360^\circ$, indicative of a spacecraft position within the outer northern current sheet or lobe, interspersed with relatively sharp minima that occur near $\Psi_N \approx \Psi_S \approx 180^\circ$, indicative of periodic excursions toward the center of the current layer. Indeed, the near-zero minimum values during the first two such oscillations indicate that the spacecraft penetrated close to the current sheet center in those cases, though to a lesser extent later in the sequence, as expected from the increasing spacecraft displacement from the center of the current sheet seen in Figure 6e.

Nonsinusoidal oscillations of the $B_\phi$ component are also evident in the tail region (Figure 6d) but are not clearly evident in the $B_\theta$ component (Figure 6c). To aid consideration of the relative phasing between the modulations of the three field components, we have divided up the interval of distinct oscillations into red and blue stripes corresponding to times when $B_r$ rises and falls with time, respectively. The precise timing of the boundaries can be somewhat uncertain given the noisiness of the field data particularly during minima, but the assignments have been aided here (and in later data figures) by computation of running 1 h field averages (not shown), which sufficiently smooths the fluctuations. Examination of the $B_\phi$ modulations shows a relatively consistent pattern in which the azimuthal field falls rapidly from peak positive to peak negative values across the intervals in which the spacecraft penetrates into the current layer, followed by a slower rise back toward near-zero and positive values during the broad $B_r$ maxima. It is thus clear that the
Turning now to our model results, we note that we have not attempted to make a detailed optimization for each individual Rev but have instead sought one set of model parameters that gives a reasonable representation for all Revs dependent only on the beat phase $\Delta \Phi$, thus clearly demonstrating the expected beat phase effects arising from the two PPO oscillations combined. Specifically, we have used $k = 2$ on the basis of the results of Provan et al. [2016] as discussed above, together with the same current sheet parameters as employed in Figure 3 (see particularly the third row for $k = 2$, Figure 3c et seq.). That is, in equation (3) we use an undisturbed current sheet half-width $D = 2.5$ $R_S$ together with northern and southern thickness modulation amplitudes of $D_N = 1$ $R_S$ and (for $k = 2$) $D_S = 0.5$ $R_S$, while in equation (2) we use northern and southern north-south oscillation amplitudes of $z_N = 2$ $R_S$ and (for $k = 2$) $z_S = 1$ $R_S$. On the basis of the results in Figure 6e, we also take (for simplicity) a fixed spacecraft position $z = +2.5$ $R_S$ near the northern edge of the undisturbed main current sheet (equation (5) and Figure 2), as shown by the green lines in the field plots in Figure 3. For the results specifically related to Rev 219 we also choose beat phase $\Delta \Phi = 330^\circ$, close to the Provan et al. [2016] value at a radial distance $\sim 20$ $R_S$ near the center of the oscillation interval (Figure 6a).

Results are shown in Figure 7, where Figure 7a shows the two PPO phases $\Psi_N$ (blue) and $\Psi_S$ (red) modulo $360^\circ$, together with the beat phase difference $\Delta \Phi = 330^\circ$ (dashed line), plotted versus $\Psi_N$ used as a time proxy over three cycles, in a format similar to Figures 3a, 3e, 3i, and 3m and Figure 6a. Figure 7b shows the three model normalized spherical polar field components, $B_\phi$ (red) derived from equations (2)–(5), $B_\theta$ (green) from equation (7), and $B_z$ (blue) from equation (8c). For purposes of plotting we have used $\alpha_\theta = 1/3$ in equation (7) for normalized $B_\theta$ as indicated in section 2.2, while comparison with the data in Figure 6d suggests that $\alpha_\theta = 1/3$ is also a suitable round value in equation (8c) for normalized $B_\phi$ (positive corresponding to the quasi-uniform field value in this case). Normalized $B_\theta$ and $B_\phi$ are plotted relative to the same (black solid) zero line toward the bottom of the panel, while for clarity normalized $B_z$ is plotted relative to the red dotted zero line on a twice times larger scale in the upper part of the plot. The normalized $B_\phi$ component oscillates about the value of unity representing the background magnetospheric field (green dashed line), while for the normalized $B_\theta$ component we show both the total value (blue solid line) and the sweepback component alone (blue dashed line), the latter just being the normalized $B_\theta$ component with inverted sign (equation (8a)). Vertical dotted lines mark maxima and minima of $B_\phi$. As expected (as in Figure 6b) maxima in $B_\phi$ occur close to $\Psi_N \approx 0^\circ$ modulo $360^\circ$ and minima near $\Psi_N \approx 180^\circ$ modulo $360^\circ$, though because of the slight departure of the beat phase from exact in-phase conditions the maxima are displaced to larger $\Psi_N$ phases (larger times) by $\sim 3^\circ$ and the minima to smaller phases by $\sim 11^\circ$, such that the fall time of the $B_\phi$ modulation is slightly shorter than the rise time in this case, with a fall time/rise time ratio of $\sim 0.85$.

Comparison of the model normalized field variations in Figure 7 with the data in Figure 6 shows reasonable overall agreement. Similar to Figure 6b, the $B_\phi$ profile shows broad positive maxima together with relatively sharp minima reaching weakly negative values, resulting from a spacecraft position near the northern edge of the undisturbed current sheet (model $z = 2.5$ $R_L$) combined with an oscillation of sufficient amplitude to carry it to the center of the sheet (and slightly beyond) when the sheet is maximally displaced to the north (model in-phase amplitude $3 R_L$), and into the northern near-lobe region of more weakly varying field surrounding the narrower primary current sheet (see Figure 2 and equation (5)) when it is maximally displaced to the south. As discussed in section 2.2, it is the presence of the wider secondary current sheet in the model that produces rounded rather than flat-topped $B_\phi$ maxima in Figure 7b, as clearly present in the $B_\phi$ variations in Figure 6b (and subsequent related figures). The model $B_\phi$ minima are not as sharp as the observed minima, however, indicative of a main current sheet of somewhat smaller half width in this case than that employed in the model ($D = 2.5$ $R_L$). We note that a small fall time/rise time asymmetry is also present in the $B_\phi$ data in Figure 6b similar to that in the model in Figure 7b arising from the slight departure from exact in-phase conditions ($\Delta \Phi = 330^\circ$), with a ratio, e.g., for the two central field oscillations (defined by the red and blue stripes) of $\sim 0.8$.

The model normalized $B_\phi$ field shows only small oscillations about unity in Figure 7b (compared with those shown for other beat phases in later figures), resulting from the near antiphase condition between the two PPO-related $B_\phi$ oscillations, which for $k = 2$ reduces the combined oscillation to half that of the dominant
northern system (i.e., to a thickness oscillation of amplitude 0.5 \( R_S \) between minimum and maximum values of 2 and 3 \( R_S \), respectively). Correspondingly, no clear modulations are observed in the \( B_\theta \) data in Figure 6c. The model normalized \( B_\varphi \) field in Figure 7b also shows how the azimuthal perturbation field of the two PPO systems (quasi-uniform field) combines with the sweepback field to produce an asymmetric nonsinusoidal modulation similar to that in Figure 6d. Specifically, across each \( B_\varphi \) minimum, \( B_\varphi \) first rises from near-zero values to a positive maximum before falling relatively sharply to a negative minimum. It then rises more slowly again toward near-zero values across the broader \( B_\varphi \) maxima, as observed in Figure 6d. 

Figure 7. Plots showing model normalized magnetic field modulations versus dominant northern phase \( \Psi_N \) used as a time proxy over three oscillation cycles, for beat phase \( \Delta \Phi = 330^\circ \) corresponding to Rev 219. (a) PPO phases \( \Psi_N \) (blue) and \( \Psi_S \) (red) modulo 360°, together with the beat phase \( \Delta \Phi \) (dashed line), in a format similar to Figure 3a et seq. and Figure 6a. (b) The three model normalized spherical polar field components, \( B_r \) (red line, equations (2)–(5)), \( B_\theta \) (green line, equation (7) with \( \alpha_\theta = 1/3 \)), and \( B_\varphi \) (blue line, equation (8c) with \( \alpha_\varphi = +1/3 \)). Normalized \( B_\theta \) and \( B_\varphi \) are plotted relative to the same black solid zero line toward the bottom of the figure, while normalized \( B_r \) is plotted on a 2 times larger scale relative to the red dotted zero line. Normalized \( B_\theta \) oscillates about unity (green dashed line) representing the undisturbed magnetospheric field, while for normalized \( B_\varphi \) we show both the total value (blue solid line) and the sweepback component alone (blue dashed line, equation (8a)). Vertical dotted lines mark the maxima and minima of \( B_r \). The model parameters employed in equations (2)–(5) for \( B_r \) are north/south PPO amplitude ratio \( k = 2 \), current sheet half-width \( D = 2.5 \ R_S \), northern and southern thickness modulation amplitudes \( D_N = 1 \ R_S \) and \( D_S = 0.5 \ R_S \), and northern and southern north-south oscillation amplitudes \( z_N = 2 \ R_S \) and \( z_S = 1 \ R_S \). On the basis of Figure 6e, we also take a fixed spacecraft position \( z = +2.5 \ R_S \) near the northern edge of the undisturbed main current sheet.
3.2. Rev 218

Figure 8 shows data from Rev 218 in the same format as Figure 6, again covering a 4 day interval starting at periapsis, for which significantly different beat phase conditions apply compared with Rev 219. In this case the transition between the core region and the tail current sheet is somewhat obscured by a data gap, but the spacecraft was clearly measuring tail-like fields dominated by positive $B_r$ after the beginning of DOY 188 at a radial distance of $\sim 18 R_S$. As can be seen from Figure 8a, the interval corresponds to one of near-quadrature of the two PPO oscillations with a beat phase $\Delta \Phi \approx 120^\circ$ during the interval of oscillations, such that the northern phase leads the southern. As noted in section 2.2 in relation to Figure 3k, this phase difference corresponds to the near-optimum condition for the presence of a sawtooth $B_r$ profile for $k = 2$ [Cowley et al., 2017], with a fast rise and slow fall in this case. This asymmetry is clearly present in the data in Figure 8b, as emphasized by the consistently narrower red stripes where $B_r$ rises with time, compared with the blue stripes where $B_r$ falls. The average rise time/fall time ratio, e.g., for the two central oscillations marked by the stripes, is $\sim 0.65$. As in Figure 6, the peaks in $B_r$ occur close to where $\Psi_N \approx 0^\circ$ modulo 360°, but the minima occur between the points where $\Psi_N$ and $\Psi_S$ pass sequentially through 180° modulo 360°. The presence of this
asymmetry under these beat phase conditions provides strong evidence for dual modulation of the tail current sheet by the two PPO systems. Other differences with Rev 219 are that the $B_{\text{min}}$ do not generally fall to near-zero and negative values as they do in Figure 6b, indicative of a smaller north-south oscillation amplitude away from in-phase conditions as expected, together with the clear presence of PPO-related modulations in $B_{\theta}$ in Figure 8c, with peaks that occur near the $B_{\text{min}}$. Periodic but nonsinusoidal modulations in $B_{\phi}$ are again seen in Figure 8d, which are similar in form to those for Rev 219 in Figure 6d, suggestive of the combination of a modulated sweepback field combined with a more direct PPO-related quasi-uniform field contribution.

Modeling results for Rev 218 are shown in Figure 9, in the same format as Figure 7 and using the same model parameters except for a beat phase $\Delta \Phi = 120^\circ$. The $B_{\text{r}}$ profile shows asymmetric modulations of the expected form with a faster rise and slower fall, with maxima that are displaced only $\sim 6^\circ$ earlier in phase than $\Psi_{\text{N}} = 0^\circ$ modulo 360° but minima that are displaced $\sim 23^\circ$ later than $\Psi_{\text{N}} = 180^\circ$ modulo 360°, similar to the data in Figures 8a and 8b, such that the rise time/fall time ratio is $\sim 0.7$. In addition, the $B_{\theta}$ modulations are of significantly larger amplitude than for Rev 219, in line with Figure 8c, with values maximizing toward the end of the slow fall in $B_{\theta}$, where the model current sheet thickness therefore also maximizes, and minimizing just before the maximum in $B_{\theta}$, where the model current sheet thickness therefore minimizes. The model $B_{\phi}$ behavior

Figure 9. Plots showing model normalized magnetic field modulations versus northern phase $\Psi_{\text{N}}$ for beat phase $\Delta \Phi = 120^\circ$, corresponding to Rev 218. The format is the same as that in Figure 7.
(again with $\alpha_\phi = +1/3$) also shows a similar modulation to that in Figure 7b, with near-zero maxima occurring at nearly the same time as $B_\theta$ maxima slightly before $B_r$ minima, and minima occurring somewhat before $B_r$ maxima, again in rough accord with the data in Figure 8d.

### 3.3. Rev 217

Figure 10 similarly shows the 4 day postperiapsis interval for Rev 217, in the same format as Figure 6, for which the beat phase has the opposite near-quadrature condition to that in Figure 8, with $\Delta \Phi \approx 240^\circ$ such that the dominant northern PPO oscillation lags the southern oscillation by $\sim 120^\circ$. The transition between the core and tail data is again obscured by a data gap, but tail field oscillations are again clearly present after the middle of day 168 at radial distances beyond $\sim 15 R_S$. In this case the opposite asymmetry is evident in the $B_r$ oscillations in Figure 10b compared with Figure 8b as indicated by the relative widths of the red and blue stripes in the figure, as expected on the basis of the results in Figure 3. The radial field now shows a slower rise to maxima occurring at times slightly later than when $\Psi_N \approx 0^\circ$ modulo $360^\circ$ in Figure 10a and a faster fall to minima near or slightly earlier than when $\Psi_N \approx 180^\circ$ modulo $360^\circ$. The fall time/rise time in this case is somewhat variable but averages to $\sim 0.5$. Modulations of relatively modest amplitude are also observed in $B_\theta$ in

**Figure 10.** Plot showing PPO, magnetic field, and spacecraft position data over a 4 day outbound interval starting at the periapsis of Rev 217. The format is the same as that in Figure 6.
Figure 10c, with maxima indicative of a thicker current sheet occurring near the beginning of the slow rise in $B_r$, rather than at the end of the slow falls as in Figure 8c, and with smaller values indicative of a thinner current sheet generally being present during the faster falls. The form of the $B_\phi$ perturbations in Figure 10d, during the earlier well-marked oscillations at least, is also somewhat different from that in Figures 6d and 8d, with a broad minimum occurring during the slow rise in $B_r$ then peaking at small positive values around the more rapid fall.

Corresponding model results are shown in Figure 11, using the same model parameters as in Figures 7 and 9, but with a beat phase of $\Delta \Phi = 235^\circ$. The model results for $B_r$ in Figure 11b show a similar slow rise-fast fall asymmetry as the data in Figure 10b, with maxima displaced $\sim 5^\circ$ later in phase than $\Psi_N = 0^\circ$ modulo 360° and minima displaced $\sim 22^\circ$ earlier than $\Psi_N = 180^\circ$ modulo 360°, such that the model fall time/rise time ratio is $\sim 0.7$. The model $B_\phi$ results also show how the sweepback effect together with the direct PPO oscillatory field (again with $\alpha_\nu = +1/3$ corresponding to the quasi-uniform field) now combine to produce a broad minimum spanning the slow rise and maximum in $B_r$, followed by a near-zero maximum toward the end of the faster fall, similar to the observed field during the initial prominent asymmetric oscillations in Figure 10d. This contrasts somewhat with the combined behavior for the opposite sense of near-quadrature.
asymmetry in Figure 9b (and for near-in-phase conditions in Figure 7b), which tends to produce a more sawtooth $B_\phi$ behavior.

3.4. Rev 220

Figure 12 shows the 4 day post periapsis interval from Rev 220, in the same format as Figure 6, for which the two PPO systems are close to antiphase as can be seen in Figure 12a. We recall that in this condition the north-south oscillations associated with the $B_r$ field perturbations for the two PPO systems should partly cancel, while the thickness modulations associated with $B_\theta$ should add. Comparison particularly with the data for Rev 219 in Figure 6, for which the two systems are approximately in phase, with opposite expected behaviors, correspondingly shows significantly weaker oscillations in $B_r$ in Figure 12b (and in $B_\theta$ in Figure 12d) within the postperiapsis core region extending into weaker $B_r$ modulations within the tail marked by the red and blue stripes but with prominent $B_\theta$ modulations in Figure 12c compared with the weak indistinct variations for Rev 219. Compared with Rev 219, the $B_r$ modulations in the tail show narrower maxima close to $\Psi_N = 0^\circ$ modulo 360° (and $\Psi_S = 180^\circ$ modulo 360°) and broader minima close to $\Psi_N = 180^\circ$ (and $\Psi_S = 0^\circ$), with maxima in $B_\theta$ near to the minima in $B_r$ as expected. The $B_\theta$ modulations in the tail region in Figure 12d show a positive
maximum near $B_r$ minimum and $B_{\theta}$ maximum, followed by a slow fall to a negative minimum shortly before the next $B_r$ minimum, and then a rapid rise again to near-zero and positive values. The overall form of the observed $B_r$ modulation is thus more sawtooth than sinusoidal but of the opposite sense to that for Revs 219 in Figure 6d and 218 in Figure 8d.

Modeling results for Rev 220 with beat phase $\Delta \Phi = 165^\circ$ in Figure 13 show reasonable qualitative agreement with the $B_r$ and $B_{\theta}$ variations, with weaker quasi-sinusoidal model modulations of $B_r$ compared with other Revs, most notably Rev 219, together with large antiphase modulations in $B_{\theta}$. As in Figure 12, the maxima in $B_r$ occur close to $\Psi_N = 0^\circ$ modulo 360° and the minima close to $\Psi_N = 180^\circ$, though due to the small departure of the model beat phase from strict antiphase, the model $B_r$ maxima are displaced to earlier phases by $\sim 2^\circ$ while the minima are displaced to later phases by $\sim 8^\circ$, such that the rise time/fall time ratio is $\sim 0.9$, similar to the average for the data in Figure 12 (average for the first two oscillations is $\sim 0.85$). Best model agreement with the $B_r$ data in this case is obtained using $\alpha_\phi = -1/3$ in equation (8c) corresponding to the quasi-dipolar sense of the PPO-related azimuthal perturbation field.

Figure 13. Plots showing model normalized magnetic field modulations versus northern phase $\Psi_N$ for beat phase $\Delta \Phi = 165^\circ$, corresponding to Rev 220. The format is the same as that in Figure 7, except that for the azimuthal component (blue line in Figure 12b) we use $\alpha_\phi = -1/3$ in equation (8c) corresponding to the quasi-dipolar sense of the PPO-related azimuthal perturbation field.
3.5. Earlier Related Revs 211–216

We now overview observations on other related Revs for which the outbound nightside portion of the orbit was sufficiently close to the equatorial plane to allow extended contact with the oscillating plasma/current sheet, similar to those discussed above. As indicated at the beginning of section 3, the overall data set can be divided into two main intervals, the first spanning Revs 211–220 (mid-January to late August 2015), for which \( k \approx 2 \) conditions generally apply as determined from the core region PPO phase analysis of Provan et al. [2016], while the second corresponds to Revs 221–230 (early September 2015 to mid-January 2016) for which this analysis indicates \( k > 5 \). In this section we discuss data from the earlier interval for which \( k \approx 2 \) (though with some exceptions as noted below), culminating in the four Revs 217–220 examined in sections 3.1–3.4. Data from the later interval for which \( k > 5 \) will be discussed in section 3.6.

In more detail, the core region phase analysis of Provan et al. [2016] indicates that \( k \approx 2 \) conditions prevailed during the periapsis passes of Revs 211–214 and Revs 217–220 (sections 3.1–3.4) but that the PPOs reverted to southern-dominant conditions \( (k < 1) \) for Rev 215, indicative of a temporary reduction in amplitude of the northern PPO and enhancement in amplitude of the southern PPO (the overall amplitude was comparable with other Revs as seen in their Figure 6). Conditions for following Rev 216 were not discussed by Provan et al. [2016] due to a prolonged core region data gap, but as shown below, examination indicates that essentially no oscillatory PPO effects were present during the outbound tail pass in this case, again indicative of short-term Rev-to-Rev PPO amplitude variations (timescales of \( \sim 20–30 \) days). Despite these significant amplitude variations, however, the PPO phases appear to have behaved essentially continuously across this interval [Provan et al., 2016].

We now discuss the tail data for the six earlier Revs 211–216 occurring prior to those discussed in detail above and in Figure 14 show four representative examples, including the two “anomalous” Revs 215 and 216, in the same format as Figure 6. We note that the spacecraft apoapsis was located north of the equatorial plane on the first three of these orbits, Revs 211–213, but was successively lowered by Titan encounters such that the orbit remained closely equatorial (as during Revs 217–220) on and after the outbound pass of Rev 213. Figures 14a–14e show data for Rev 211, the first in the sequence to exhibit extended contact with the oscillating plasma sheet as apoapsis was lowered toward the equatorial plane. The large sharp field perturbations seen in Figures 14b–14d as the spacecraft crossed the equatorial plane at a radial distance of \( \sim 20 \) \( R_s \) (Figure 14e) is due to the Titan encounter. On this nightside pass the northern and southern PPOs were near in phase, with a beat phase \( \Delta \Phi \approx 50^\circ \) as seen in Figure 14a. The approximately additive nature of the northern and southern north-south plasma/current sheet oscillations under this condition no doubt contributes to the extended sequence of tail field oscillations observed at radial distances beyond \( \sim 18 \) \( R_s \), despite the increasing displacement of the spacecraft northward of the equatorial plane and the expected center of the current sheet with increasing radial distance (Figure 14e). Even so, the implied individual oscillation amplitudes in this case are rather larger than employed above. Near \( \sim 25 \) \( R_s \), for example, the combined oscillation is seen to be sufficient to carry the current sheet across the spacecraft between near its northern boundary and its center, which given the expected undisturbed displacement at that time in Figure 14e implies a total oscillation amplitude of \( \sim 5 \) \( R_s \). Given \( k \approx 2 \) and the above oscillation phase difference, the northern and southern amplitudes in this case are thus estimated to be \( \sim 4 \) and \( \sim 2 \) \( R_s \), respectively. Overall, however, the field oscillations are seen to be very similar in form to those for Rev 219 in Figure 6 under similar beat phase conditions, with near-symmetrical oscillations in the \( B_x \) component, small and less distinct perturbations in \( B_y \), and periodic nonsinusoidal variations in \( B_y \) indicative of the combined effect of an oscillating sweepback field and a direct PPO perturbation. We note, however, that the \( B_z \) rise times are generally slightly shorter than the fall times in Figure 14b, as indicated by the red and blue stripes (averaged rise time/fall time \( \sim 0.9 \)), consistent with beat phase \( \Delta \Phi \approx 50^\circ \), opposite to the small related effect for Rev 219 (averaged fall time/rise time \( \sim 0.8 \)) in Figure 6b with \( \Delta \Phi \approx \sim 30^\circ \) noted in section 3.1.

Data for following Rev 212 are shown in Figures 14f–14j, for which the beat phase is \( \sim 230^\circ \), corresponding to near-quadrature conditions with the southern phase leading the northern, similar to Rev 217 in Figure 10. Here the \( B_z \) oscillations are much less prominent than for Rev 211, indicative of a smaller combined amplitude, but still show a slower rise and faster fall behavior as for Rev 217 (averaged fall time/rise time ratio \( \sim 0.7 \) compared with \( \sim 0.5 \) for Rev 217), with \( B_y \) similarly somewhat elevated during the \( B_z \) rises (red stripes) and depressed during the falls (blue stripes), indicative of dual PPO modulation.
The following two passes, Revs 213 and 214 (data not shown), represent near repeats of Revs 211 and 212, with beat phases ~50° and ~270°, respectively. Correspondingly, the $B_r$ oscillations for Rev 213 are found to be similar to those on Revs 211 and 219 under similar near in-phase conditions, exhibiting an extended sequence of north-south oscillations of the current sheet, while those for Rev 214 are again more muted but also show evidence of slower rise/faster fall behavior similar to Rev 212 together with $B_\theta$ and $B_\phi$ perturbations similar to Revs 212 and 217. While the data for these four nightside passes thus exhibit less varied conditions than for Revs 217–220 (sections 3.1–3.4), with no further examples of near antiphase or near quadrature north leads south conditions, they nevertheless continue to display properties consistent with dual north-south modulation of the tail plasma/current sheet.

In Figure 15 we now turn to the anomalous Revs 215 and 216. Figures 15a–15e show data from Rev 215, for which Provan et al. [2016] determined southern-dominant PPO conditions within the core region as indicated above. In this case the beat phase is ~105° (Figure 15e), such that the two PPO oscillations are expected to be near quadrature with the northern phase leading the southern, similar to Rev 218 in Figure 8. Although a somewhat attenuated sequence of tail field oscillations is observed on this pass, the $B_r$ component does not exhibit the same fast rise/slow fall profile as observed during Rev 218. Instead, the $B_r$ oscillations are more symmetrical in form with peaks occurring just prior to $\Psi_S \approx 0°$ modulo 360° conditions and exhibit an averaged fall time/rise time ratio defined by the red and blue stripes of ~0.9, compared with a rise time/fall time ratio of ~0.65 for Rev 218. The $B_\phi$ oscillations are essentially in antiphase, while the $B_\theta$ behavior is mixed. Data for Rev 216 are similarly shown in Figures 15f–15j, for which (given the extended core region data gap) the interpolated phases indicate near in-phase behavior with beat phase ~345° (Figure 15f). In this case we might expect additive north-south displacement amplitudes to give rise to an extended sequence of

Figure 14. Plots showing PPO, magnetic field, and spacecraft position data over 4 day outbound intervals starting at the periapsides of (a–e) Rev 211 and (f–j) Rev 212. The formats are the same as that in Figure 6, except that the ranges of the field data in both $B_r$ panels (Figures 14b and 14g) and the $B_\phi$ panel for Rev 212 (Figure 15i) have been slightly altered to better accommodate the data (the overall scale remains fixed at 15 nT across each panel).
large-amplitude current sheet oscillations similar to Revs 211, 213, and 219, while contrarily the field data in Figures 15b–15d show no clear PPO-related oscillations in any of the field components, indicating the temporary cessation of PPO activity at this time (though resumed at usual levels on following Rev 217 shown in Figure 10). Overall, the data from Revs 215 and 216 thus demonstrate that the PPOs can show significant short-term modulations in both northern and southern amplitudes, although as indicated above the PPO phases appear to have varied nearly continuously across this interval [Provan et al., 2016].


We now consider the data for later near-equatorial Revs 221–230, after which the orbit plane once more became increasingly tilted with apoapsis in the northern hemisphere. During this interval, no southern PPO modulation effects could be discerned in the core region superposed on the dominant northern PPO oscillations, thus implying a north/south amplitude ratio $k$ greater than $\sim 5$ [Provan et al., 2016]. However, weak modulations continued to be observed in southern SKR emissions during this interval, allowing continued determination of the southern PPO phase. Figures 3d, 3h, 3l, and 3p correspondingly show that under such conditions we also expect the tail plasma/current sheet oscillations to be dominated by the northern PPOs, with little dependence on the beat phase. In this case, the north-south oscillation amplitude should be essentially independent of whether the southern PPO is in phase or in antiphase with the northern PPO, and no oppositely signed sawtooth effects should be evident for opposite near quadrature conditions. Here we thus discuss the tail data from Revs 221–230 in relation to these expectations.

On the first of these passes, Rev 221 (data not shown), for which the orbit remained similar to that for Rev 219 in Figure 5, the two PPO systems were inferred to be closely in phase. As expected, clear near-symmetrical oscillations were observed in $B_n$, though of lesser amplitude than for Revs 211 in Figures 14 and 219 in
Figure 6 and with weak antiphase modulations in $B_\theta$ indicative of northern phasing. After this Rev, however, the spacecraft orbit became modified while remaining closely equatorial, with a reduced apoapsis at $\sim 32 \, R_S$ at $\sim 4.2 \, h \, LT$, compared with $\sim 45 \, R_S$ at $\sim 3.6 \, h \, LT$ for Rev 219 in Figure 5. Consequently, passage through the relevant radial distance range $\sim 15$–$25 \, R_S$ took place at significantly later LTs nearer the dawn magnetospheric flank. On these passes the current sheet oscillations were found generally to be somewhat less evident in terms of amplitude and radial extent than those discussed in sections 3.1–3.4. While the physical reason for this remains unclear, we note that prior examination by Andrews et al. [2010a] of preequinox equatorial PPO amplitudes correspondingly found peak amplitudes on the nightside, falling toward both dawn and dusk to weaker values on the dayside. This suggests an effect associated with the day-night asymmetry imposed on Saturn’s magnetosphere by the solar wind flow, such that the PPO power radiated from two polar ionospheres propagates preferentially downtail. Despite the overall weaker PPO-related effects, study of the oscillations observed on these passes, as anticipated, reveals no clear evidence for dual modulation effects, such as differences in the overall amplitude

Figure 16. Plot showing PPO, magnetic field, and spacecraft position data over a 4 day outbound interval starting at the periapsis of Rev 227. The format is the same as that in Figure 6.
between cases where the oscillations are expected to be near in phase (e.g., Revs 224 and 228) and those which are near antiphase (e.g., Revs 222 and 226), or sawtooth modulations for Revs where the oscillations are expected to be near quadrature (e.g., Revs 223, 225, and 227). An example of the latter condition is shown in Figure 16 for Rev 227, where again we show 4 days of postperiapsis data in the same format as Figure 6, during which the beat phase is very similar to Rev 218 in Figure 8. Although oscillations are clearly present in the $B_r$ and $B_\phi$ components within the core region, the oscillations in $B_r$ beyond ~15 $R_S$ do not reveal a similar fast rise slow fall asymmetry as in Figure 8 and subsequently become indistinct at radial distances beyond ~20 $R_S$. As for the core region data examined by Provan et al. [2016] on these periapsis passes, there is thus no evidence in these data for the presence of a significant southern PPO component, unlike for Rev 218 in Figure 8. Corresponding modeling results are shown in Figure 17, where we use beat phase $\Delta \Phi = 130^\circ$ from Figure 16a, together with the same model parameters as in previous modeling figures but now with $k = 5$. Here the sawtooth asymmetry is barely evident in the $B_r$ profile, as expected, with a rise time/fall time ratio of ~0.9, opposite in sense to the modest asymmetry in the similarly quasi-sinusoidal oscillation in the observed $B_\phi$ profile in Figure 16b.

Figure 17. Plots showing model normalized magnetic field modulations versus northern phase $\Psi_N$ for beat phase $\Delta \Phi = 130^\circ$, corresponding to Rev 227. The model parameters are related to those in Figures 7, 9, 11, and 13, with fixed position $z = +2.5$ $R_S$, half width $D = 2.5$ $R_S$, northern thickness modulation amplitude $D_N = 1$ $R_S$ and northern north-south oscillation amplitude $z_N = 2$ $R_S$, while now we take $k = 5$, such that $D_S = 0.2$ $R_S$ and $z_S = 0.4$ $R_S$. We also take $\alpha_\phi = +1/3$. The format is the same as that in Figure 7.
4. Summary

We have presented near-equatorial Cassini tail data from 2015, specifically from Revs 211–230 spanning from mid-January 2015 to mid-January 2016. This interval corresponds to Saturn’s northern spring, during which the amplitude of the northern PPO system was initially about twice that of the southern system to late August of 2015, after which the amplitude of the southern system declined further to become less than one fifth of that of the northern [Provan et al., 2016]. Clear PPO-related modulations of the tail plasma/current sheet are generally observed on these passes but limited to radial distances inside ~25–30 Rₖ due to the seasonal tilting of the center of the current sheet south of the equatorial spacecraft orbital plane. Four sequential passes during the initial interval have been selected for detailed study, Revs 217–220 spanning mid-June to late August, for which midnight sector tail modulations were well marked and displayed a near-ideal set of relative PPO phases, near in phase and antiphase, as well as opposite near-quadrature conditions. These data have also been compared with an augmented version of the mathematical model introduced by Cowley et al. [2017], in which simple normalized forms for all three spherical polar field components have been introduced depending on the two PPO phases. It was found that clear sawtooth effects in the radial field with expected opposite senses were observed during the two opposite near-quadrature conditions, fast rise and slow fall when the northern phase led the southern, and slow rise and fast fall when the southern led the northern, thus showing that these effects are present and can be discerned and modeled under conditions when the north/south amplitude ratio is ~2. It was also found that the values of the colatitudinal field were generally elevated during the "slow" compared with the "fast" radial field behaviors, consistent with the model dependency and the expectation that the plasma/current sheet is thicker during the former intervals than the latter. Examination and modeling of the azimuthal field shows that the observed behavior can be described approximately as the sum of a direct PPO-related component (corresponding to the quasi-uniform field region for three out of four cases) plus a sweepback field component associated with subcorotation of the magnetospheric plasma. Only weak sawtooth asymmetry effects were found to be present for both the near in-phase and antiphase cases, as expected. However, the modulations of the radial field were found to have significantly larger amplitude for in-phase conditions than for anti-phase, and while the colatitudinal field modulations were well marked for antiphase (having opposite sense to the radial field variations) they were essentially absent for in phase. These findings are thus in line with the expectation that the north–south oscillations associated with the radial perturbation field of the two systems reinforce each other for in-phase conditions, while the thickness modulations associated with the colatitudinal perturbation field of the two systems partly cancel, and vice versa for antiphase conditions.

Examination of data from the earlier interval for which the north/south PPO amplitude ratio was ~2, corresponding to Revs 211–214, shows general agreement with the above picture, in particular with large amplitude north–south oscillations for near in-phase conditions on Revs 211 and 213. Overall, however, these four Revs exhibit less varied beat phase conditions with correspondingly somewhat less striking beat phase effects. Core region and tail data from following Revs 215 and 216 instead provide evidence for short-term (Rev-to-Rev) variations in the northern and southern PPO amplitudes, however, with the southern PPO oscillations becoming temporarily dominant during Rev 215, and with no PPO-related tail oscillations being evident at all on Rev 216 following a prolonged core region data gap. In the later interval corresponding to Revs 221–230 when the amplitude of the southern PPO system had declined further to a factor of at least ~5 less than the northern, however, no clear dependency of the tail field modulations on the beat phase was then evident. In particular, no clear differences were discerned in the north–south oscillation amplitudes between in-phase and antiphase conditions, and no clear sawtooth effects were observed for near-quadrature conditions. This is again as expected under conditions in which the field perturbations are sufficiently dominated by a single PPO system, in this case the northern system.

References


