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An update to a Saturnian longitude system based on kilometric radio emissions

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[1] The period of Saturn kilometric radiation modulation as determined by Voyager forms the basis for a longitude system (SLS) recognized by the International Astronomical Union. However, Ulysses and Cassini observations have shown that this modulation period varies by the order of one percent on timescales of a few years and, hence, does not represent the internal rotation period of the planet. A new longitude system was proposed based on ~2 years of Cassini observations of the kilometric radio emissions and accounts for the variable radio period (SLS2) valid over the time interval from day 001, 2004 through day 240, 2006. Early uses of this longitude system have revealed a number of magnetospheric phenomena which appear to be locked to the radio period, such as variations in the external magnetic field, the plasma density in the inner magnetosphere, and enhanced intensities of energetic ions. Analysis of the radio emissions since the new system was proposed revealed that the radio period continued to evolve, even showing a second, shorter period at times. The subsolar longitude of the peak of Saturn kilometric radio emissions begins to deviate from that given by the SLS2 system almost immediately after the previous analysis interval. Here, we provide a definition for SLS3, an extension to the longitude system valid over the interval from day 001, 2004 through day 222, 2007 based on variable period radio emissions.

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1. Introduction

[2] The period of Saturn kilometric radiation (SKR) modulation as determined by Voyager forms the basis for a longitude system recognized by the International Astronomical Union (IAU) [*Seidelmann et al.*, 2002] sometimes referred to as the Saturn Longitude System or SLS. *Desch and Kaiser* [1981] found a period of 10 h, 39 min, 24 ± 7 s (10.6567 h) based on Voyager observations in the 1980 era. However, Ulysses and Cassini observations have shown that this modulation period varies by the order of one percent on timescales of a few years [*Lecacheux et al.*, 1997; *Galopeau and Lecacheux*, 2000; *Gurnett et al.*, 2005], hence, does not represent the internal rotation period of the planet. Furthermore the IAU system does not serve well to organize Cassini observations since the 1% difference in period grows to differences in longitudes of more than a rotation after only several weeks. A new longitude system was proposed by *Kurth et al.* [2007] (hereafter referred to as K2007) based on ~2 years of Cassini observations of the kilometric radio emissions and accounts for the variable radio period. Since this system, like the SLS system, is based on the modulation period of Saturn kilometric radiation we herein refer to this system as Saturn kilometric radiation longitude system 2, or SLS2. Early uses of this longitude system have revealed a number of magnetospheric phenomena which appear to be locked to the radio period, such as variations in the external magnetic field, the plasma density in the inner magnetosphere [*Gurnett et al.*, 2007], hot spots in energetic neutral atom images, and others [e.g., *Carbary et al.*, 2007].

[3] Since it is clear that the modulation of SKR, with a variable period, cannot represent the rotation of the deep interior of Saturn, one might wonder why a longitude system based on it should be developed. However, as mentioned above, such a longitude system does organize a number of magnetospheric phenomena observed by Cassini, something the Voyager SLS system cannot do. This is reason enough to develop and maintain such a system. However, there are other uses for such a system as well. For example, Voyager observations of the formation of spoke features in Saturn's rings were found to be organized by the SLS system, both in period and in phase [*Porco and Danielson*, 1982]. In fact, the Cassini imaging team is using SLS2 and even a preliminary version of the system presented here to study features in the rings [M. Hedman, personal communication, 2007]. The fact that the variations in the SKR period cannot be predicted means that the system must be updated to support studies of more recent Cassini observations.

[4] The technique used by K2007 to track the evolving SKR modulation period involved finding the drift in phase

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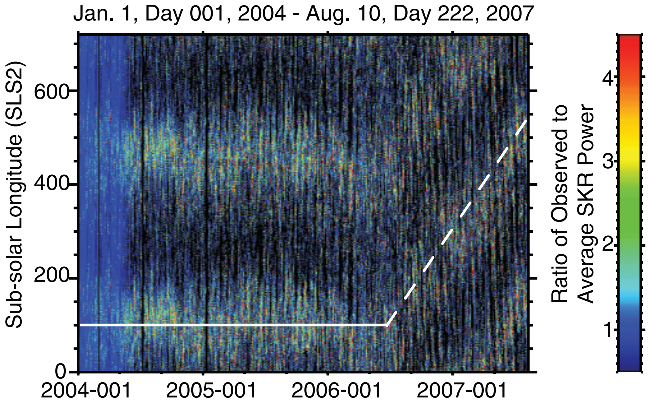

Figure 1. A plot of the normalized intensity of SKR as a function of time and subsolar longitude based on the SLS2 longitude system defined by K2007. Each vertical strip in the figure represents the intensity of SKR integrated over the range from 50 Hz to 500 kHz normalized to the rotation-averaged integrated intensity and is represented by color per the color bar on the right. After normalizing, data from four rotations are averaged to improve the signal-to-noise. Data from 0–360° in longitude are repeated in the range of 360 to 720° for clarity. The system is valid as long as the peak of the SKR is centered at 100° (at the position of the white line). Note that in mid-2006 the phase of this peak begins to drift to larger values (as shown by the dashed white line), indicating that the third-order fit to the phase variance with respect to an arbitrarily chosen fixed period no longer matches the data after this time.

of the SKR peak as a function of time relative to a somewhat arbitrarily chosen fixed period. The technique also used the Voyager result that Saturn kilometric radiation is clock-like; the local time of the observer with respect to Saturn does not appear to affect the time at which the observer sees the peak in SKR emissions. Hence the SLS2 longitude system was designed such that the SKR peak occurs when the subsolar longitude is 100°, as was the case in the Voyager era. The phase variation relative to a fixed period was fit with a third-order polynomial. This technique avoids having to integrate over a large number of inaccurately known periods in order to find the longitude at any specific time as one might have to do for a series of Fourier transforms of the SKR data. Such integration leads to the possibility of losing or gaining a full rotation if the period is not known accurately enough. It should also be pointed out that by fitting the phase variation over timescales of years with a low-order polynomial guarantees that shorter timescale variations in the SKR period will be smoothed. Recently, *Zarka et al.* [2007] reported on short timescale variations of the SKR period (of the order of weeks or less) that may be associated with solar wind influences on the generation of SKR. Certainly, such short period variations can explain some of the scatter in the SKR phase as a function of time found both by K2007 and herein.

[5] The interval over which SLS2 was valid extended from 1 January 2004 through 28 August 2006. At the time, it was not known how well the cubic fit to the phase variations would continue to track SKR peaks after that time. Figure 1 shows that the SLS2 phase began to deviate from the fit almost immediately and that, within a few months, the difference in phase given by the fit and the actual SKR observations was of the order of 100 degrees. The horizontal white line is at a longitude of 100° while the white dashed line is sketched to indicate the trend of the SKR longitude drift beyond day 240, 2004. Figure 1 uses a false color scheme to show the normalized SKR intensity as a function of subsolar longitude from the new system and time; the longitude axis extends to 720° and the data from 0–360° are repeated from 360 to 720° for clarity. Each vertical strip in the figure represents the intensity of SKR integrated from 50 to 500 kHz normalized to the rotation-averaged intensity. Data from four rotations are averaged to improve the signal-to-noise. It should be noted that while SKR intensities can vary by tens of decibels on timescales of several minutes, the 'diurnal' modulation often is only a factor of two or so, hence, a relatively weak signal.

[6] K2007 also reported that near the end of their analyzed interval the visibility of the modulation peak was quite poor and this made fitting the phase variation quite difficult. Among factors that may have contributed to this lack of visibility were the orbit of the spacecraft, including local time and latitude, both of which had varied considerably in the latter portion of 2006, and temporal variations in how well the radio emission is organized by the planet's rotation. *Lamy et al.* [2008] have shown that Cassini, on average, has observed weaker SKR in the dusk sector than at other local times, hence, orbital variations could be contributors to the visibility of the rotational modulation, as well. We investigate this, further, in the discussion.

[7] In view of the above, in the present work we have extended the interval for the SKR longitude system to 10 August 2007. In doing this extension, we were concerned about two major factors. First, the visibility of the rotational modulation discussed above made it quite difficult to be sure that the SKR phase peak was being tracked, properly. The appearance of a second period significantly shorter than the one tracked so far in the Cassini mission and even shorter than the Voyager period further complicated the work. We have modified our analysis to improve this situation. Second, we wanted to do the extension in such a way that work performed using the SLS2 system would not have to be redone.

2. Analysis

[8] Figure 1 shows that the visibility of the SKR peak is diminished in the latter part of 2006, but the situation improves in more recent times. In addition to the visibility decreasing, it is also apparent that the width of the SKR peak becomes broadened. Over the timescales analyzed, the phase variation drifts through multiple 360-degree ranges relative to a fixed period, although the sine wave fit employed to find the peak necessarily works only in the range of 0–360°. Hence to fit the peak using the method followed by K2007, one needs to be able to follow the peak from one 360° range to the next as a continuous function. As the peak becomes less well defined and broader, this becomes more difficult because the identification of a given peak moving from one 360-degree range to the next can become ambiguous. To the extent that peaks are associated

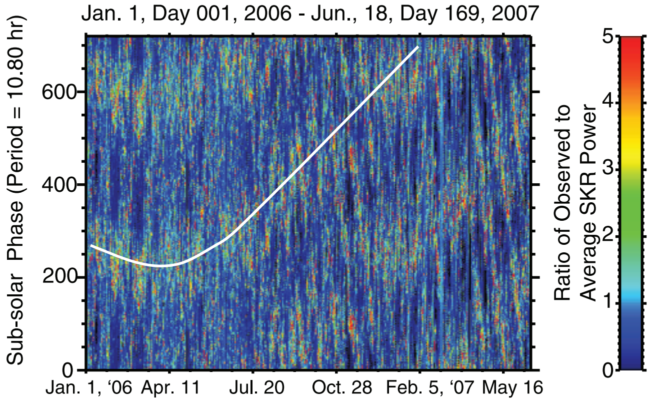

Figure 2. A plot constructed in a manner similar to that in Figure 1, but for the interval from day 001 of 2006 through day 222 of 2007. In this analysis, instead of using the K2007 phase correction, we simply chose a fixed period of 10.80 h. Notice that while this does reveal a slowly drifting peak which becomes horizontal around April 2006, indicative of a period at or near 10.80 h, there are also rapidly drifting diagonal bands, suggesting a second period.

with the incorrect 360° range, the data points used for the fit become suspect.

[9] Another issue became apparent in late 2006. Careful inspection of the spectrogram in Figure 1 reveals a set of rapidly drifting bands superimposed on the slowly drifting phase peak. This pattern is reminiscent of a vertical hold issue in older television sets. With the assumption that an organized pattern of drifting bands represents a relatively coherent period in the data, we attempted to see if such a second period exists in addition to the one upon which the SLS2 system is based. First, in Figure 2, we replot the data from the latter part of the interval shown in Figure 1 choosing a fixed period of 10.80 h. This period was chosen using trial-and-error to find a fixed period which shows the phase drift exhibiting a region of zero slope. The phase of the SKR peak has a local minimum, or horizontal region, in April 2006, hence, is evidence that the period was about 10.80 h for a time, surrounded by somewhat different periods before and after. This is within the range of periods tracked by the SLS2 system. The rapidly drifting diagonal bands in the latter portion of the plotted interval are even more apparent in Figure 2 because of the expanded time-scale. After some trial and error, we found that if we used a period of about 10.59 h that the diagonal bands would become nearly horizontal. This is shown in Figure 3. In this presentation, the slowly drifting pattern is evidence of a period near 10.59 h, but now the rapidly drifting pattern is due to the longer period (near 10.8 h) modulation.

[10] To confirm the second period, we applied the spectrum analysis technique devised by *Gurnett et al.* [2007] which fits a sine wave to the normalized SKR amplitude by successively sweeping the period and looking for periods which give the maximum amplitude for the sine fit. Figure 4 shows examples using data from a series of 2-month long intervals from day 244 of 2006 through day 182 of 2007 in panels a through e. In this figure, strong peaks are observed at rotation rates of about 800 and 815°/d (corresponding to periods of about 10.8 and 10.6 h, respectively). Other peaks are seen in these spectra, which we attribute to beat effects as suggested by *Gurnett et al.* [2007] due to relatively small sampling statistics. Panel f in Figure 4 tends to confirm this in that it covers an 11-month interval and the peaks near 800°/d (10.8 h) and 815°/d (10.6 h) are the only two which appear to be statistically significant. It is clear that for some intervals shown in Figure 4 that the 800°/d rotation rate (10.8 h period) dominates, while in others the 815°/d (10.6 h) peak is the strongest.

[11] The upper panel of Figure 5 demonstrates the variation in rotation rate for the two SKR periods as a function of time using a series of analyses like those in Figure 4. Two-month sliding intervals, slid by 1 month for each interval, were analyzed from 1 January 2004 through 1 August 2007. The series of black dots refer to the longer period signal, approximately the period responsible for the SLS2 longitude system. The black line is the rotation rate derived from the analysis of the drift of the longer period signal presented in the next section. The red dots show the variation in the rotation rate for the new, shorter period signal when it could be clearly identified in the spectra. The lower panel of the figure shows the relative strength of the two peaks by showing the amplitude of the sine wave fit for the respective peaks like those shown in Figure 4. The lower amplitudes for the ~800°/d signal in early 2004 are due to the large distance of Cassini from Saturn as it approached Saturn during the latter portion of its cruise to the planet. Clearly, the amplitude of this signal decreases with time after 2004, reflecting the decrease in visibility pointed out by K2007. They suggested two possible explanations for the decreasing signal-to-noise in the modulation, including the evolving orbital geometry of Cassini or simply a temporal change in the magnitude of the modulation, but came to no firm conclusion. Prior to 2006, the newer, short period is barely visible. However, for the latter part of 2006 and into 2007, the short period signal is often stronger than the longer period one. There is evidence for a strong short period peak through the extent of the 2007 data analyzed herein.

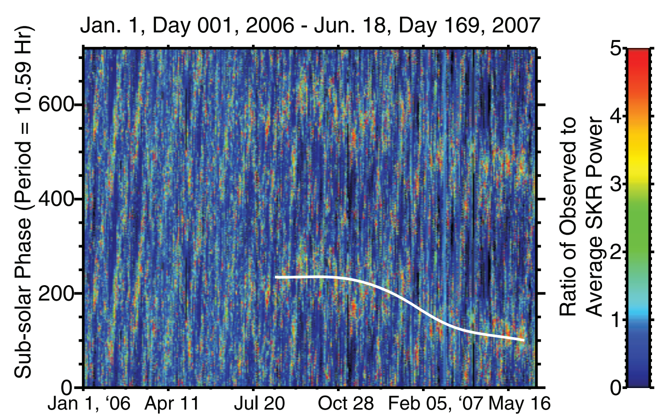

Figure 3. A plot identical to Figure 2, with the exception that the analysis was done using a fixed period of 10.59 h. Notice that using this much shorter period, nearly horizontal bands are also found, suggesting a second period near 10.6 h.

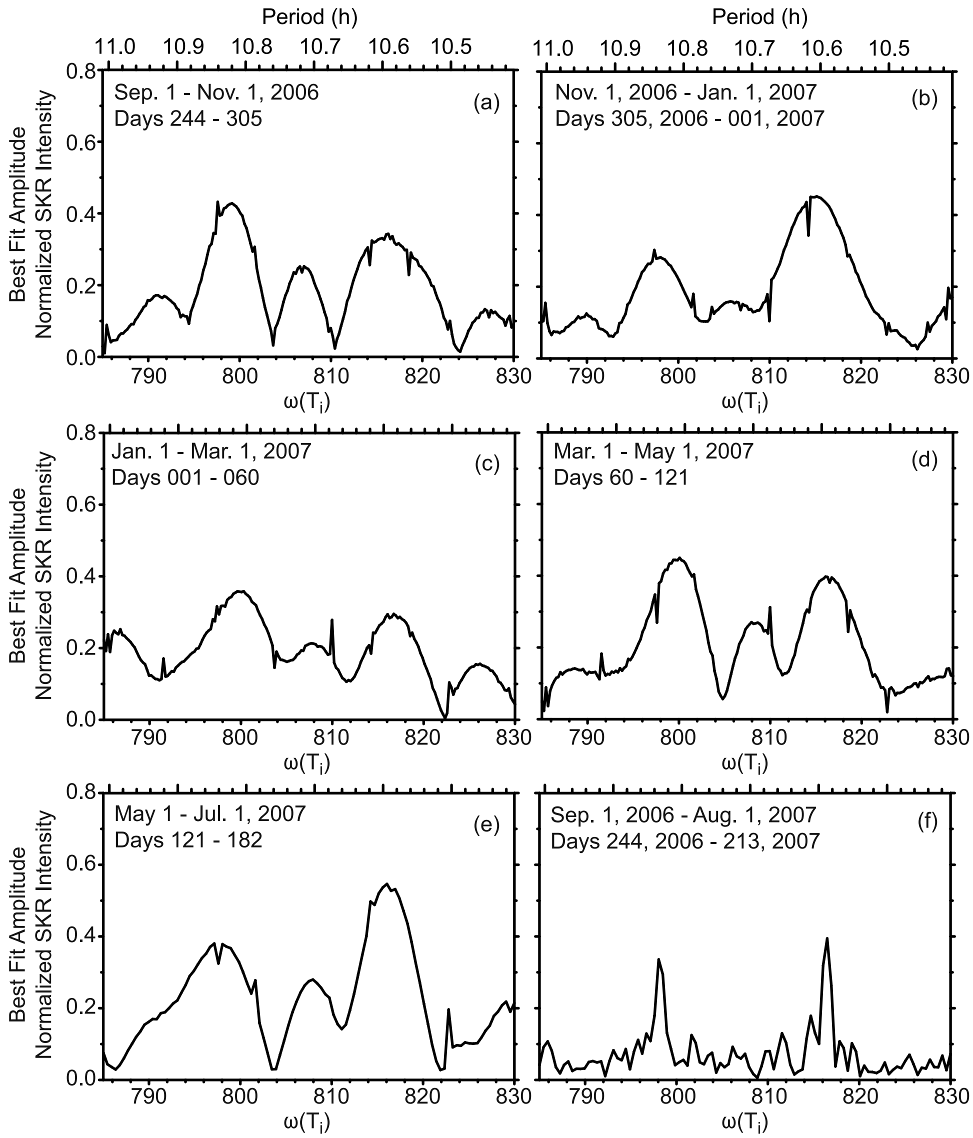

Figure 4. Analyses of the type devised by *Gurnett et al.* [2007] that show the amplitudes of a sine wave fit to SKR data using different rotation rates from 785 to 830°/d (corresponding to periods of 11.064 to 10.4096 h). Strong peaks suggest a component of the period at the respective rotation rate exist in the data. In panels a–e there is evidence for rotation rates near both 800 and 815°/d (periods of 10.8 and 10.6 h) with one peak dominating during some intervals and the other dominating at other times. Panel f is the result of an analysis interval covering 11 months that shows both peaks with nearly equal amplitude.

[12] In spite of the appearance of the second period, the apparently smooth variation in the phase drift of the longer period signal (e.g., as seen in Figure 2) suggests that we should be able to continue to track the phase of that signal, even though there are periods where it becomes quite weak. That is, there are times when both periods are present in the modulation of SKR, but the periods are sufficiently different that we can isolate the phase variation of the longer period and track it. Therefore we proceed with the analysis of the longer period signal in order to extend the SLS2 longitude system of K2007. It is likely possible to construct a different longitude system for the shorter period and perhaps this should be done. However, the focus of this paper is to extend the SLS2 system based on the longer period.

[13] Given that a primary issue with developing the SLS2 longitude system had to do with decreased visibility of the rotational modulation signal late in 2006, we have adapted the analysis of the SKR phase to improve the signal-to-noise ratio of the modulation. Since our analysis ignores short term variations such as those reported by *Zarka et al.* [2007] (and, in fact, these short term variations provide some of the spread in the data), we averaged data over about 10 days to decrease the spread in the phase of the peak. Specifically, we assumed a period of 10.7928 h and averaged over 22 rotations, for an averaging interval of 9.8934 days. The 10.7928-h period was used by K2007 because it minimized the range of the phase drift over the interval they studied and we simply adopted that period for this analysis. K2007 used 4-rotation averages in their analysis. Hence the new

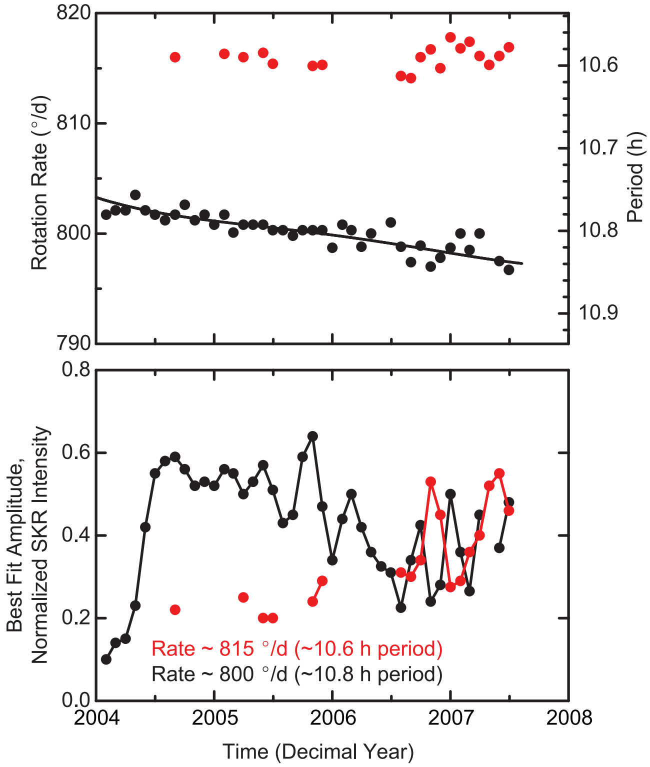

Figure 5. Upper panel: Using analyses similar to those shown in Figure 4 for a series of 2 month analysis intervals slid by 1 month for each time step (like a sliding, 2-month average), we have plotted the rotation rate corresponding to the two largest peaks in the spectrum. The series in black dots near 800°/d (10.8 h period) correspond to the slower period used for the SLS2 longitude system. The series of red dots correspond to the shorter period peak near 815°/d (10.6 h period). Overplotted on the ~800°/d (10.8 h) data is the period derived from the SLS3 longitude system defined herein. Lower panel: A plot of the sine wave amplitude for the peaks near 800 (black) and 815 (red) °/d (corresponding to 10.8 and 10.6 h periods, respectively). Notice that the amplitude of the two peaks vary with respect to one another, suggesting that one peak dominates for a while, and then the other. Evidence for the new, shorter period signal persists through the end of the interval.

approach employs a factor of 5.5 more data in an average, which should reduce the spread by about a factor of 2.

[14] Figure 6 shows the phase of the ~10-day average SKR peaks as a function of time. In fact, the analysis gives the phase with a modulus of 360°, hence, as the phase drifts, discontinuous jumps appear in the phase. For Figure 6 we have subtracted or added multiples of 360° to later values in order to obtain the smooth curve in this figure.

[15] A third-order polynomial can be fit to the data in Figure 6 (red curve), in the same way K2007 fit the earlier interval. The constants for this fit are given in Table 1, along with those of K2007. However, since the timescale for the extended data set is longer, and new data are included at the end, the match of such a fit deviates by nearly 40° from the K2007 fit at the beginning of the interval (1 January 2004). Should we adopt such a fit for the extended longitude system, deviations of this magnitude would be found between the old and new system for some periods of time. This would likely require considerable work for users of the old system to continue their work, essentially forcing them to re-analyze earlier data.

[16] To avoid drastic changes in SKR longitude for times covered by the SLS2 system, we have applied a 5th order polynomial fit to the data in Figure 6. This fit, defined in the next section, is plotted in green in Figure 6 along with the K2007 fit (in black). The 5th order fit replicates the original system quite well as is shown in Figure 7, which plots the phase used for SLS2 less the phase derived from the 5th-order fit. Note that for the interval analyzed by K2007, the differences are about 10° or less. K2007 reported that their fit had an uncertainty in the constant term of about 9°, hence, any other fit within about 10° of theirs should be an equivalent representation of the data.

[17] Users, then, can adopt the extended system defined herein, SLS3, without changing their results by a statistically significant amount. However, some may be uncomfortable with this solution. Hence an alternate approach would be to use the SLS2 system up to a point, and then use the new system. To avoid an abrupt phase shift, one should move the switch-over point to the last point in time that the two fits match. This occurs on day 98 of 2006. Since the derivative of this phase function (plus a constant term) gives the rotation rate, using the switch-over method will result in a discontinuous change in the period, because the slope of the two curves is not identical where the phases match. We will refer to this hybrid system, using SLS2 followed by the SLS3 for the more recent data SLS3′.

3. The Extended Longitude System SLS3

[18] In this section we define the extended longitude system SLS3 based on the modulation of the Saturn kilometric radiation. Our method follows K2007.

[19] For a planet with a fixed rotation period, longitude is a simple function of time:

$$\lambda = C_0 + \omega_0 T \tag{1}$$

where λ is longitude measured in degrees, C_0 is a constant, ω_0 is the fixed rotation period in units of °/d, and T is the time in days since some epoch time at the planet. Since the observations here are obtained by Cassini some distance $R(t)$ from Saturn, we must correct the time from the epoch T_0 at Cassini T by the one-way light time from Saturn using:

$$T = t - T_0 - R(t)/c \tag{2}$$

where c is the speed of light and t is the time at Cassini.

[20] For a variable period, equation (1) must be modified to include a phase correction:

$$\lambda_{Sun} = C_0 + \omega_0 T - \phi(T) \tag{3}$$

As was the case for SLS2, we use 1 January 2004 for T_0. K2007 used a value for ω_0 of 360°/P_0 where P_0 was rather arbitrarily chosen to be 0.44970 days (10.7928 h) in order to

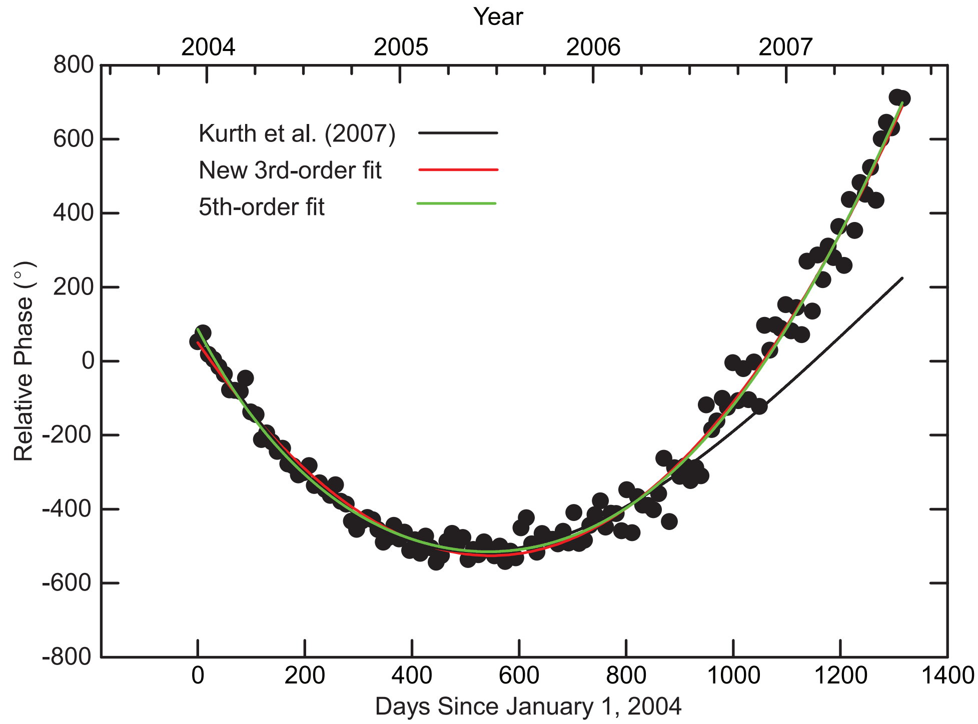

Figure 6. A plot of ∼10-day average SKR peak phase as a function of time from day 001, 2004 through day 222, 2007. For later points, multiples of 360 were subtracted or added to the originally determined phase so that the points fall along a smooth curve as shown. The spread of the points is significantly less than those used by K2007, hence, if an erroneous step of 360° was added or subtracted, the point would fall far from the curve and be simple to find and correct. The black curve is the phase fit from K2007. The red curve is a 3rd-order fit to the entire interval. The green curve is a 5th-order fit to the entire interval.

minimize the phase drift over the interval they analyzed. We use the same value for P_0. Hence the function $\phi(T)$ describes the variation of the phase of the SKR peak relative to a fixed period "rotation" of 0.44970 days (10.7928 h). Finally, SLS2 was defined such that the peak of the SKR occurred when the subsolar longitude λ_{Sun} is 100°, so this sets $C_0 = 100°$ in equation (3). The reason for defining the system in this way is because *Warwick et al.* [1981] demonstrated that the SKR appeared to act as a strobe light or brighten as seen from all directions when a particular longitude faced the Sun. In the SLS system, this was 100°, hence, both SLS2 and SLS3 are defined in the same way.

[21] To this point, our definition of SLS3 is identical to SLS2. The difference between the two, however, lies in the function $\phi(T)$. Whereas SLS2 used a cubic fit to describe the phase variation, SLS3 uses a 5th-order fit of the form

$$\phi(T) = C_1 + C_2 T + C_3 T^2 + C_4 T^3 + C_5 T^4 + C_6 T^5 \quad (4)$$

The six constants are listed in Table 1 along with the constants for the K2007 cubic fit and the cubic fit mentioned above and shown in Figure 6. The interval of time spanned by this fit is 1 January 2004 through 10 August, day 222, 2007.

[22] Figure 7 shows the difference between the $\phi(T)$ used for SLS2 and the 5th-order fit found here. SLS3 differs little from SLS2 over the interval 2004 day 001 to about 2006 day 140 (20 May). Given that the uncertainty of the fit to the phase variation given by K2007 was of order 10 degrees, the differences are statistically insignificant. Hence users of SLS2 need not be concerned about the minor variations in switching to SLS3. However, if variations of this order are bothersome, we propose that a hybrid system could be used, SLS3′, which involves using SLS2 up until 2006, day 98 (8 April) and SLS3 thereafter. On this date, the longitudes given by the two systems are identical.

[23] Equation (3) gives the sub-solar longitude λ_{Sun}. Given λ_{Sun} and the local time of the spacecraft (or other

Table 1. Fit Parameters for SLS2, the Third-Order Fit Over the Extended Interval Shown in Figure 6 and SLS3

Constant	SLS2	SLS2 Std. Error	New 3rd-Order Fit	3rd-Order Std. Error	SLS3	SLS3 Std. Error	Units
C1	87.77	10.1	50.65	14.5	86.6681	20.7	°
C2	−2.527	9.05×10^{-2}	−2.0767	9.61×10^{-2}	−2.7537	0.32	$°d^{-1}$
C3	3.041×10^{-3}	2.17×10^{-4}	1.8147×10^{-3}	1.70×10^{-4}	4.7730×10^{-3}	1.50×10^{-3}	$°d^{-2}$
C4	-7.913×10^{-7}	1.47×10^{-7}	1.0061×10^{-7}	8.50×10^{-8}	-4.8755×10^{-6}	2.96×10^{-6}	$°d^{-3}$
C5					3.5653×10^{-9}	2.48×10^{-9}	$°d^{-4}$
C6					-9.1485×10^{-13}	7.51×10^{-13}	$°d^{-5}$

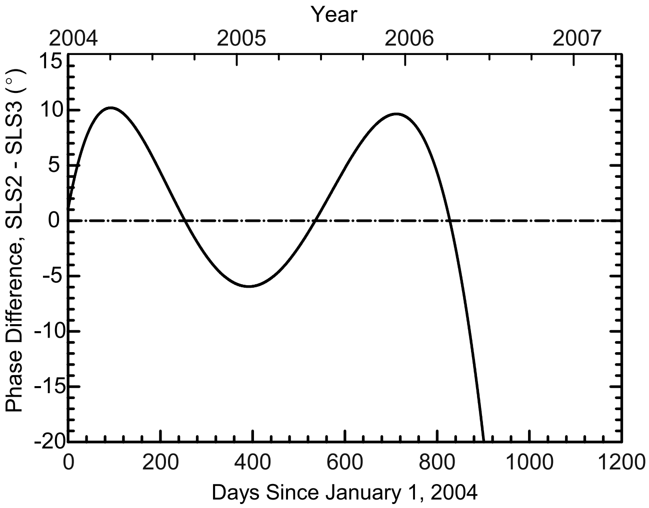

Figure 7. The difference between the phase function upon which the SLS2 system is based and the 5th-order function derived herein for SLS3. Note that for the interval analyzed by K2007, until about day 140 of 2006, the differences are about 10° or less.

body of interest) $LT_{s/c}$, the spacecraft longitude can be calculated using:

$$\lambda_{s/c} = \lambda_{Sun} + \left(12 - LT_{s/c}\right)15^\circ \tag{5}$$

[24] Figure 8 provides sample IDL code to compute both λ_{Sun} and $\lambda_{s/c}$ assuming the user has SPICE kernels and software to determine the one-way-light-time *owlt* and Cassini's local time $LT_{s/c}$.

[25] The rotation rate is given by differentiating equation (3) to determine dλ/dt. If one substitutes the fit $\phi(T)$ from equation (4), then the SLS3 rotation rate is obtained. We have overplotted the SLS3 rotation rate in the top panel of Figure 5 as the solid black line. The left-hand axis gives the rotation rate in °/d while the right hand axis gives the period in hours.

4. Discussion

[26] Figure 9 shows the SKR peak organized by SLS3 subsolar longitude. As was the case for SLS2, the SLS3 longitude system clearly organizes the SKR phase peak well in the interval from January 2004 through January 2006. It also organizes the 2007 data reasonably well. The case for the latter portion of 2006 is not as strong. The visibility is still poor in mid-2006 and there appears to be a drifting peak in the latter part of 2006. We have investigated this feature in Figure 10. Figure 10 plots the subsolar phase of the SKR peak as a function of time relative to a fixed period of 10.83 h, again using a trial-and-error method to find a fixed period which minimizes the phase drift over the limited interval. The result is a band which drifts to lower phase until early July 2006 at which time the phase remains nearly constant until November 2006 and then the band resumes its drift to lower phases. Hence there are two inflection points in this band within the space of about 4 months. Inspecting Figure 6 during this time interval (~915 to ~1050 days since 1 January 2004), there is a cluster of points with nearly fixed phase followed by a "jump" of about 180° to larger phases in this general time frame. In fact, it seems clear that the SLS2 phase function is strongly influenced by the cluster of fixed-phase points which occurred near the end of the SLS2 analysis interval (~970 days since 1 January 2004). Interestingly, this is the same general time interval during which *Carbary et al.* [2007] reported a jump of approximately 180° in the orientation of a "spiral" of enhanced intensities of 28–48 keV electrons. The phase variation during late 2006 has a time-scale that is short compared to variations that can be fit with the 5th-order polynomial in equation (4), hence, must be considered a "short time-scale" variation which we have said above are not tracked by our technique. This variation seems to be different, however, from the shorter time-scale period variations reported by *Zarka et al.* [2007].

[27] A vexing problem with this work was the fact that the visibility of the diurnal SKR peak degraded over the time of this analysis as can be seen qualitatively in Figures 1 and 9 and somewhat quantitatively in the bottom panel of Figure 5, which shows that the amplitude of the sine wave fit using the *Gurnett et al.* [2007] analysis decreased with time from late 2004 through 2006. During this time period Cassini's orbit was evolving and the spacecraft was spending more time on the dusk side of the planet and in late 2006 and early 2007 the orbit inclination increased to about 60° before returning to near equatorial on 13 June, day 164, 2007. Given the local time beaming characteristics of SKR revealed by *Lamy et al.* [2008], perhaps it is just this effect that contributes to the decreased visibility. By the end of the interval, in mid-2007, the visibility of the SLS3 phase peak (as seen in both the lower panel of Figures 5 and 9) appears to have recovered, even though the second period is often dominant in this time frame. We discuss possible orbital effects, below.

[28] Complicating matters further was the appearance and even dominance of the second peak near 815°/d (10.6 h period) late in the analysis period. The ~10-day averaging utilized in this study was meant to increase the signal-to-noise of the SKR phase peak, which it appeared to do. One can compare the spread in the SKR peak in the spectrograms (Figures 1 and 8) to the spread in the ~10-day average points in Figure 6 and note that the longer averages reduce the spread, significantly. The second period is different from the longer period tracked by SLS3 by about 2 percent. Hence over the 10-day averages, the faster modulation would spread the peak over about 160 degrees. This would tend to skew a 10-day average, but after every two or three 10-day averages, even this skewing would be eliminated. While the second period must certainly contribute to the spread in the phase peaks in Figure 6 in the latter portion of the interval, it should not affect the overall trend of the data. Further demonstration of this is that in Figure 2, a clear variation in the SKR phase using a period near that of the SLS3 period is observed, even though on a finer timescale evidence of the shorter period is visible.

[29] The second, shorter period is certainly of interest in the issue of the entire Saturn rotation period conundrum, even though this is not the central focus of this paper. The period, near 10.6 h, is the shortest period SKR modulation

```
IDL> coefs=[86.6681d0, -2.7537d0, 0.0047730d0,-4.8755d-06,
3.5653d-09, -9.1485d-13]
IDL> owlt=8.69; Saturn-Cassini one-way light time in seconds at
time t chosen to be 00:00 on Jan. 1, 2006 for this example
IDL> localtime=4.952; Local time of Cassini in hours at time t
IDL>
DeltaT=Julday(1,1,2006,0,0,0)-Julday(1,1,2004,0,0,0)-owlt/86400
% Compiled module: JULDAY.
IDL> phasedrift = poly (DeltaT, coefs)
% Compiled module: POLY.
IDL> lambdasun=360.*(1.0/0.4497)*DeltaT-phasedrift+ 100.0 ;
lambdasun is subsolar longitude in degrees
IDL> lambdasun = lambdasun mod 360 + 360*(lambdasun lt 0)
IDL> print,lambdasun
      23.247440
IDL> CassiniLong=(12.0-localtime)*15.+lambdasun
IDL> CassiniLong = CassiniLong mod 360 + 360*(CassiniLong lt 0)
IDL> print,CassiniLong
      128.96744
```

Figure 8. Sample IDL code to calculate the longitude of the Sun λ_{Sun} and spacecraft $\lambda_{s/c}$ in the SLS3 system. It is assumed that the user has access to SPICE kernels and software to determine *owlt* in seconds from Saturn to Cassini and the *localtime* of Cassini in hours for the time of interest (t = 00:00 on 1 January 2006 in this example). Note that *DeltaT* is an absolute difference in time, hence, should not include leap seconds. However, the error introduced in using UTC versus UT is negligible relative to the uncertainties in the fit parameters in equation (4).

signal reported to date, shorter than both the Voyager period and subsequent Ulysses and Cassini measurements. Given the model for the variable SKR period proposed by *Gurnett et al.* [2007] which suggests that the magnetospheric magnetic field slips due to variable mass loading from Enceladus, the implicit assumption is that Saturn's internal rotation period is faster than the SLS2 or SLS3 period. Could the new, shorter period be more closely related to the internal rotation period? *Anderson and Schubert* [2007], using a shape model from Pioneer and Voyager occultation and wind data, Cassini gravity measurements, and the assumption that Saturn's atmosphere is in a minimum energy state derive an internal rotation period of 10 h, 32 m, 30 ± 17 s (∼10.54 h), somewhat shorter than the new SKR period.

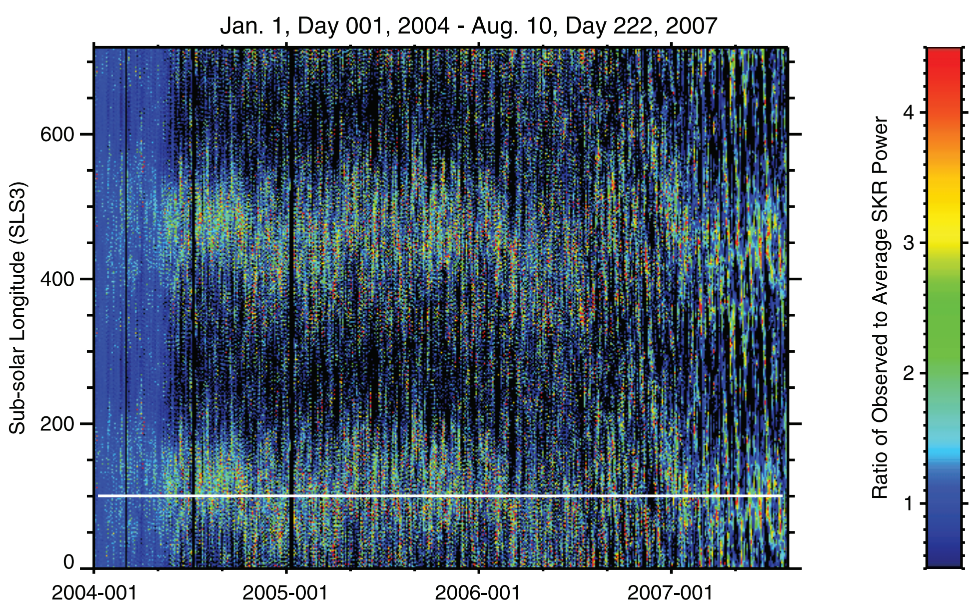

Figure 9. Plot similar to that in Figure 1, but using the SLS3 longitude system to organize the SKR peak versus subsolar longitude.

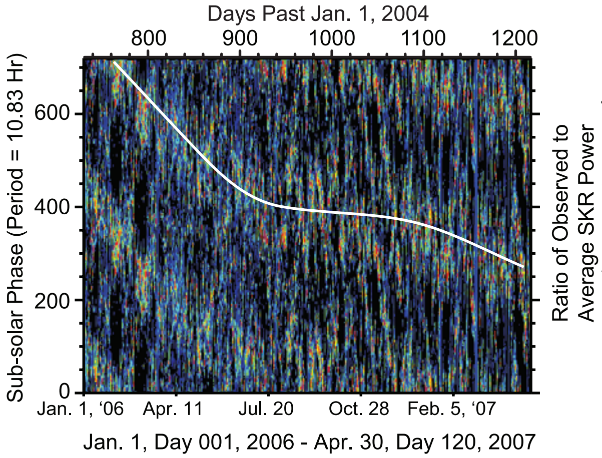

Figure 10. A spectrogram similar to that in Figures 2 and 3, but using a fixed period of 10.83 h. The white line is a sketch to highlight the drift in SKR phase. The variation of phase relative to this fixed period over the plotted interval suggests a short-term variation in the magnetospheric rotation period that the SLS3 system does not track. This short term variation explains the drift in the SKR phase peak in late 2006 apparent in Figure 9.

However, based on the upper panel of Figure 5, the new SKR period is not fixed, hence, it has the same problem as the SLS3 period in that it varies and, therefore, is less likely to represent the true Saturn rotation period. There are other possible explanations, as well. For example, Titan has been shown, recently, to exert some control over the intensity of SKR emissions [*Menietti et al.*, 2007]. Interestingly, Cassini's orbit has a period near 16 days, close to Titan's orbital period of 15.95 days, around the times of the two most intense occurrences of the shorter period, near November, 2006 and in the spring of 2007. The correspondence is not exact, however, hence, this is only suggestive. Also, *Galopeau and Lecacheux* [2000], *Cecconi and Zarka* [2005] and *Zarka et al.* [2007] have all suggested and even demonstrated that the SKR period can be modified by a variable solar wind input to the magnetosphere, leading to a secondary peak in the modulation periodogram.

[30] Both the visibility of the SKR "diurnal" peak and the appearance of the second period are possibly related to variations in Cassini's orbit. In the middle panel of Figure 11 we reproduce the bottom panel of Figure 5 with the local time of Cassini's apoapsis in the top panel and Cassini's latitude in the bottom panel. We have plotted the local time of Cassini's apoapsis because this is the portion of the orbit in which the spacecraft spends most of the time, hence, should have the strongest effect on synoptic observations. The SKR "diurnal" peak minimizes in mid-2006. During this time, the local time of Cassini's apoapsis is near midnight. *Lamy et al.* [2008] show that Cassini observes a minimum in the SKR intensity in the approximate local time range of 15 to 20 h. Cassini's apoapsis does not move into this local time range, though, until early 2007 when the visibility has recovered. While not conclusive, this would not suggest a strong correlation between the overall SKR beaming properties and the visibility of the "diurnal" peak. On the other hand, the decrease in visibility does loosely track the drift of the apoapsis local time from dawn to midnight, so perhaps there is a less direct connection between the visibility than just the local time beaming variation. Looking at the bottom panel of Figure 11, while the visibility appears to become worse from its peak after orbit insertion in mid-2004, the latitude variation does not show a monotone trend that would suggest a correlation.

[31] The appearance of the second period near 10.6 h most strongly in late 2006 and again in 2007 at first glance appears to correlate with Cassini's movement to higher inclination orbits. However, the short period signal diminishes during the middle of this high-latitude excursion and is strongly visible after the return to equatorial latitudes after day 164. We performed an analysis like those in Figure 4 using the interval of days 164–222 of 2007 to confirm this, since the granularity in the amplitude information in the center panel of Figure 11 is quite coarse. Even in this special analysis using only near-equatorial measurements, the

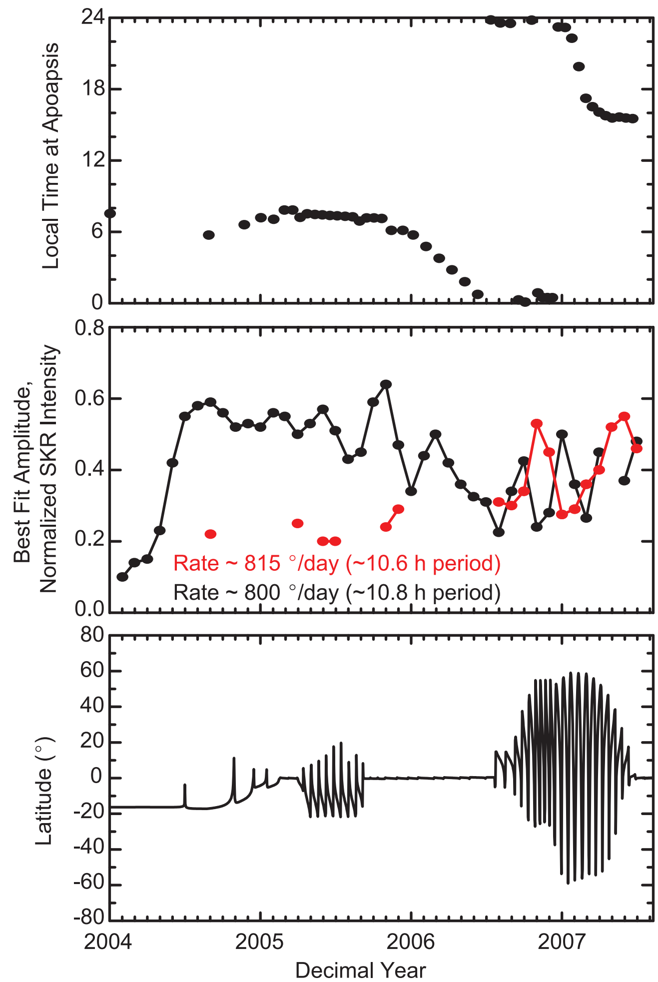

Figure 11. A comparison of the visibility of the long period "diurnal" signal corresponding to the SLS3 system and the shorter period modulation (center panel) compared to the variation in the local time of Cassini's apoapsis (top panel) and its latitude (bottom panel). The text discusses the lack of correlation between the visibility of either of the two periods observed in the SKR intensities and these orbital characteristics.

short-period peak dominates the longer period signal; it is hard to explain the appearance of the second, short-period peak by a change in observer latitude. Further, when we look for a correlation between the visibility of either of the signals with the average of the absolute value of the latitudes, the correlation coefficient is less than 0.3.

[32] K2007 were unsure of how far beyond the end of their analysis period their longitude system would be useful. It is clear from Figure 1 that within a few months of the end of the analysis interval there was a significant (several tens of degrees) difference in the cubic fit they employed and the observed SKR phase. Therefore, we assume that a similar deviation between SLS3 and the observed SKR peak will be seen on a timescale of a few months after 10 August 2007. This would seem to obviate yet additional extensions to the longitudinal system.

5. Conclusions

[33] *Gurnett et al.* [2007] have demonstrated that the SLS2 system represents the variable rotation of Saturn's magnetosphere, consequently, there is a need for such a system to organize observations in the magnetosphere. This paper presents an extension to the SLS2 system to day 222 (10 August) of 2007. Adaptations to the analysis have been made to account for the decreased visibility of the SKR "diurnal" peak in 2006 and the result is a system that organizes the SKR peak reasonably well. The primary exception to this is a short term variation in the latter third of 2006 during which the phase may deviate by as much as 180° from the model before recovering. The fact that the system does not track this short-term phase deviation is related to the 5th-order polynomial fit to the phase variations. A system with considerably higher order terms or perhaps a piecewise fit might track this more accurately, but consideration of such a system is beyond the scope of this work. The SLS3 system is designed to be statistically compatible with SLS2, but by switching from SLS2 to SLS3 on day 98 of 2006 the hybrid SLS3′ system should minimize rework by investigators who are uncomfortable with any shift in longitudes in the earlier interval. This work also identified a second period in the SKR near 10.59 h, the shortest SKR "diurnal" modulation reported to date. While we have demonstrated that the existence of this second period, which sometimes dominates the SLS3 period, does not appreciably affect the analysis leading to the definition of the SLS3 system, it certainly raises interesting questions concerning its origin and perhaps how the rotation of the magnetosphere relates to the rotation of the interior of the planet.

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