RE-VISITING SATURNIAN KILOMETRIC RADIATION WITH ULYSSES/URAP

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Abstract

Due to its excellent sensitivity, the URAP radio astronomy experiment aboard the interplanetary Ulysses spacecraft regularly detects faint radio emissions in addition to the intense bursts from the Sun. By using dedicated methods for automated dynamic spectrum analysis, we were able to prove that these emissions mainly come from Saturn and, as expected but in a lesser extent, from Jupiter. In some cases, the signal to noise ratio on Saturn kilometric radiation (SKR) is high enough to allow a detailed study of the dynamic spectrum which much resembles that of Jupiter observed from high jovigraphic latitudes. We present here a preliminary analysis of the new SKR observations and a comparison with previous Voyager results (on average flux, spectrum, periodicities, polarisation...). The strong relationship between SKR intensity and solar wind ram pressure at Saturn, is well characterised: this may provide an efficient method for monitoring the solar wind variations at 10 AU, from an observatory in the neighbouring of the Earth. The 10.7 hr occurrence period of SKR activity is found to be 1% longer than the one deduced from the previous Voyager data.

1 Introduction

All the knowledge we have about the Saturnian kilometric radiation (SKR) has been brought by the Planetary Radio Astronomy (PRA) experiment aboard the two *Voyager* spacecraft [Kaiser et al., 1984]. The available data set represents about six months of observations around the close flybys of Saturn in November 1980 and in August 1981.

The SKR is an intense non thermal radio emission, similar in many aspects to the Earth's auroral kilometric radiation (AKR) and Jupiter's decameter radio emission (DAM). Detailed properties were reviewed by [Kaiser et al., 1984]. The emission spectrum extends from a few kHz to more than 1.2 MHz and generally peaks around 200 kHz with a maximum flux density of $\sim 3 \cdot 10^{-19}$ W m^{-2} Hz^{-1}, normalised at a standard distance of 1 AU. Two components of the SKR have been detected by *Voyager 1* and *2*, in opposite senses

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of circular polarisation [Ortega-Molina and Lecacheux, 1990], with a polarisation degree near or equal to 100%. This emission is strongly modulated at the period of 10h39m24s, corresponding to the planetary rotation period (10.6567 ± 0.0002 hr [Desch and Kaiser, 1981]), but is also possibly modulated at 66 hr under the influence from the satellite Dione [Kurth et al., 1981b]. Finally the SKR exhibits a long term variability at ~ 13 and ~ 25 days periods corresponding to some control of the radio emission by the solar wind conditions at Saturn [Desch, 1982; Desch and Rucker, 1983].

Two spatially separated radio sources of the SKR have been identified [Warwick et al., 1981]. They are located in both northern and southern hemispheres, at high latitude, and are distinguished by their opposite polarisation sense. Several works about the SKR source location demonstrated that these sources do not rotate with Saturn as those at Jupiter, but are rather fixed at about noon in local time [Kaiser et al., 1981; Kaiser and Desch, 1982; Lecacheux and Genova, 1983] in the planetary dayside. Moreover, Galopeau et al. [1995] showed they extend in the morning side at $\sim 0800 - 0900$ LT. The observed modulation of the emission at the planetary rotation period then implies that the SKR preferentially emits when a particular active longitude sector passes through a specific local time.

2 The ULYSSES/URAP experiment

The *Ulysses* mission deals with the study of the heliosphere, from a trajectory mainly located out of the ecliptic plane. The spacecraft, built by ESA, was launched in late 1990 and put, in February 1992, on its final, high inclination orbit by gravity assist at Jupiter. The *Ulysses* spacecraft is planned to remain in operation well beyond the year 2000, after at least two complete orbits around the Sun.

Ulysses carries nine plasma instruments provided by scientific teams both from USA and Europe. In this study, the radio astronomy, high frequency part (Hi-RAR) of the Unified Radio and Plasma waves instrument (URAP) was only considered. A description of the complete instrument is given in Stone et al. [1992a].

The URAP/Hi-RAR radio astronomy antenna system consists of a wire dipole antenna (X), 72 m tip to tip, and of a 7.5 m monopole antenna (Z), respectively perpendicular and parallel to the spacecraft spin axis. The Hi-RAR sub- instrument consists of two very sensitive, sub-heterodyne radio receivers, which analyses the frequency band 52 to 940 kHz, and can be connected to the X and Z antennas in three different electric configurations: one receiver is connected to the (Z) monopole; the other one is connected to either the spin-plane (X) dipole alone or to both spin-plane and spin-axis antennas in summation mode (S); at the output of each receiver the signal is sampled much faster than the satellite spin period (one full rotation in about 12 second). With this scheme, in addition to measurements of the received power, an estimate of both direction of arrival and polarisation of the received signal can also be get, by Fourier analysing the modulation of the receiver outputs at the spin frequency. Detailed descriptions of the general method can be found in Lecacheux [1978], Manning and Fainberg [1980] and several examples of applications to the planetary case in Reiner et al. [1993a] and Ladreiter et al. [1994].

In the following, we will show that the unprecedented sensitivity of the interplanetary URAP/RAR radio astronomy experiment [Lecacheux et al., 1992] allied with its direction finding capability allows to continuously monitor several radio sources in the solar system, namely the active Sun, and the planets Jupiter and Saturn, even at quite large distance from these bodies.

3 Data analysis

In spite of the high sensitivity of the receivers, the URAP experiment uses simple wire, low directivity antennas and hence the planetary events, viewed far from their sources, have a poor contrast above the noise background. Above about 400 kHz, the main contribution to the background noise is due to the galactic emission, whose brightness distribution is not uniform in the sky, and hence produces a signal slightly modulated by the spacecraft rotation. Below about 400 kHz, e.g. in most of the available frequency channels, the background noise is dominated by the local plasma noise which depends on the solar wind activity and whose intensity level changes at time scales ranging from minutes to days. It is therefore not practicable to use a simple, intensity threshold detection scheme.

Our detection scheme is rather based on the assumption that local plasma noise does not produce any sinusoidal modulation of the receiver output, related to the spacecraft spin period, and hence that the presence of such a modulation is the signature of an incoming radio wave. On the other hand, while the galactic emission produces also an antenna modulated signal, the modulation is constant over a long time scale (it is only slowly changing along the *Ulysses* heliocentric orbit as a function of the orientation of the spacecraft spin axis) and hence can be removed.

In our detection method, the utilised criteria is the amplitude of the modulation relative to the measured mean intensity of the signal, the so-called “modulation index” τ_M. For each frequency channel, the “quiet” value of τ_M is computed by averaging data over 24 hours: instantaneous τ_M are then compared with the quiet value and those significantly different are flagged as candidate events.

For the candidate events, the origin of the radio wave is further deduced from the comparison of the intensity modulation profile with the expected antenna response to a point source radiating from the infinite. In principle, whatever the antenna configuration is (see above), the modulated signal get a minimum when the radio source direction lies in the meridian plane containing the spinning antenna: the corresponding azimuth in the spin plane is then compared with those of solar system bodies computed from the astronomical ephemeris and spacecraft navigation data. In the real case, a much refined analysis must be carried out because of several sources of error.

Specifically, the URAP/RAR receiver analyses twelve frequency channels, log-spaced from 52 kHz to 940 kHz. One complete frequency scan is done every 144 seconds. One frequency step lasts exactly 12 seconds, approximately equal to the duration of the spacecraft spin period. Eight equidistant data samples are acquired during each frequency step and describe the modulation profile with a resolution of 1.5 second (as shown below).

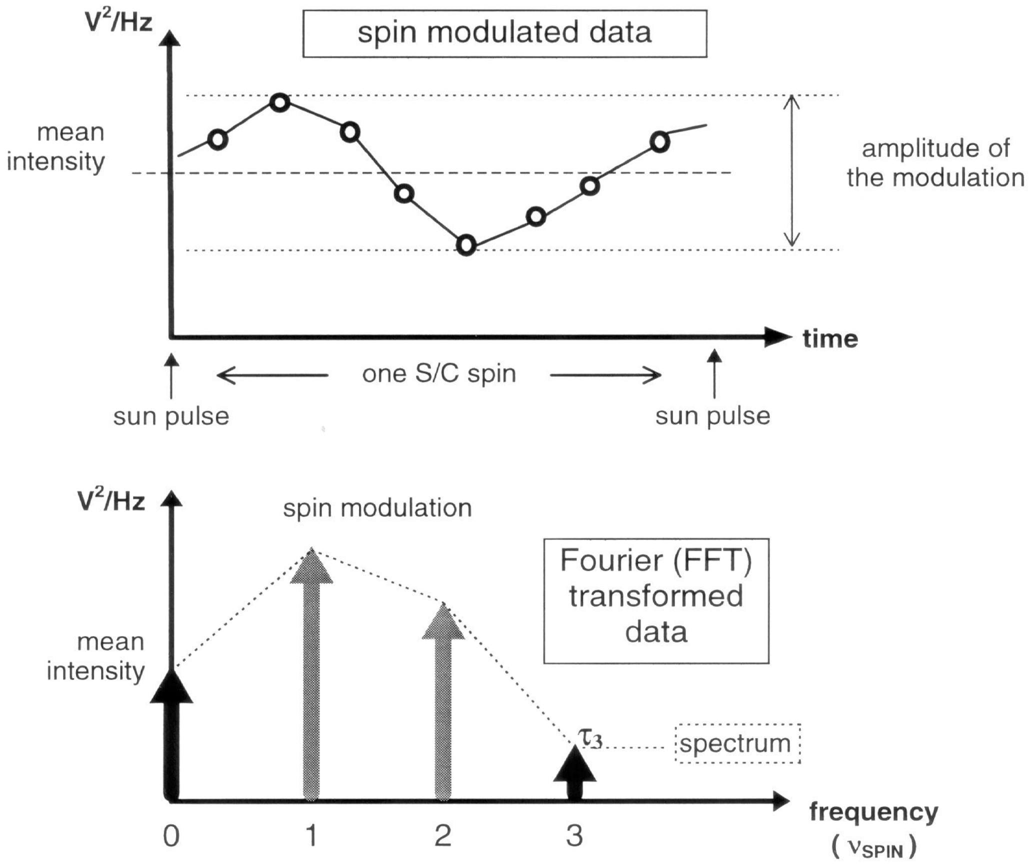

Figure 1: Sketch explaining the relationship between the time modulation parameters of the spin modulated signal (top) and the first Fourier components of its spectrum (bottom). The third harmonics of the spin frequency may serve to check whether the incoming signal varies slower or faster than the s/c rotation and, therefore, can be used or not for direction and polarisation retrieval.

Working in the Fourier space (Figure 1), the eight real data samples are transformed in four complex numbers which describe the power spectrum of the signal at the discrete frequencies $k{\cdot}\nu_{SPIN}$, $k = 0, 1, 2, 3$ and $\nu_{SPIN} = 1/12$ Hz. The amplitude τ_0 (at frequency 0) is equal to the mean signal intensity over the spin period; the amplitudes τ_1, τ_2 and phases φ_1, φ_2 at the frequencies ν_{SPIN} and $2\,\nu_{SPIN}$ describe the spin modulation and contain the available information on the incoming radio wave(s); finally, the Fourier component at the frequency $3\,\nu_{SPIN}$ contains an important piece of information: if the incoming signal is steady, it must be equal to zero (amplitude $\tau_3 = 0$, phase random). In other words, the condition $\tau_3 \neq 0$ expresses that the incoming signal does have actually fluctuated faster than 12 seconds and, consequently, that the spin modulation information cannot be safely utilised.

Without enter in further unessential details, the outline of the corresponding data analysis and classification software can be summarised as follows:

- step 1: *extraction of the events*
  - Fourier transformation (FFT) of the calibrated, original data

  - coherent integration of the wave forms over 144 seconds
  - detection of events by detection of significant changes in the modulation index τ_M

- step 2: *classification of the events*
  - checking signal stability over 12 seconds (by using τ_3)
  - if stability condition is fulfilled, retrieval of direction (polarisation) informations from $\tau_1, \tau_2, \varphi_1, \varphi_2$
  - comparison of the deduced source azimuth, measured in the antenna frame, with directions of solar system bodies as computed from astronomical ephemeris (within tolerance of $\pm 15°$ for planets and $\pm 30°$ for the Sun).

- step 3: *further identification of ambiguous events* (neighbouring directions)
  - by additional criteria (dynamic spectrum, polarisation, etc.)

In this study, we have applied the method to the 578 days of URAP/RAR data, ranging from Nov. 1, 1994 to May 31, 1996. The data base contains $578 \times 600 \times 12$ spin samples, averaged over 144 seconds. The following table summarises the result of our classifying algorithm:

class	type of activity	number of samples	percentage
1	none	4 017 685	96.55
2	unidentified	33 789	0.81
3	solar	27 650	0.66
4	Jovian	27 849	0.67
5	Saturnian	22 144	0.53
6	undecided solar/Jovian	23 954	0.58
7	undecided solar/Saturnian	8 362	0.20
8	undecided Jovian/Saturnian	11	0.00
9	undecided solar/Jovian/Saturnian	156	0.00
	total	4 161 600	100.00

Table 1: Classification of the radio events detected from Nov. 1, 1994 to May 31, 1996.

Taking the $52 - 940$ kHz frequency band as a whole, a significant level of radio emissions could be detected 23% of the time, 4.2% being identified as coming from Saturn and 5.1% from Jupiter.

The detailed analysis shows that more than 3% of the time-frequency plane contain events from solar or planetary origins. In Table 1, the "undecided" events correspond to solar or planetary emissions which occurred when mentioned bodies were in conjunction and could not be clearly separated by direction finding analysis. The "unidentified" events likely belong to solar, Jovian or Saturnian classes but displayed intensity variations within a spin period and therefore could not be identified by direction finding analysis. Most of them exhibit polarisation, hence likely come from Jupiter or Saturn. In the remaining, in order to retrieve firm properties of the Saturnian radiation, we only take into account the events belonging to class 5, i.e. those unambiguously identified as coming from Saturn.

4 SKR properties: occurence, spectrum and polarisation

Figure 2 and 3 summarise the relative positions of *Ulysses*, Jupiter and Saturn in the heliocentric, ecliptic reference frame, during the studied period (Nov. 1, 1994 to May 31, 1996). As viewed from Saturn, *Ulysses* remained in the Saturnian dayside, at distance ranging from about 8 to 13 AU, and at low latitude (less than 15°), both north and south, from the ring plane. This is, basically, the same geometry than along the Voyager 1 and 2 inbound trajectories, except for the larger distance. Therefore, one would expect, after intensity correction for the distance, to retrieve all the SKR properties already observed by Voyager and reviewed by Kaiser et al. [1984].

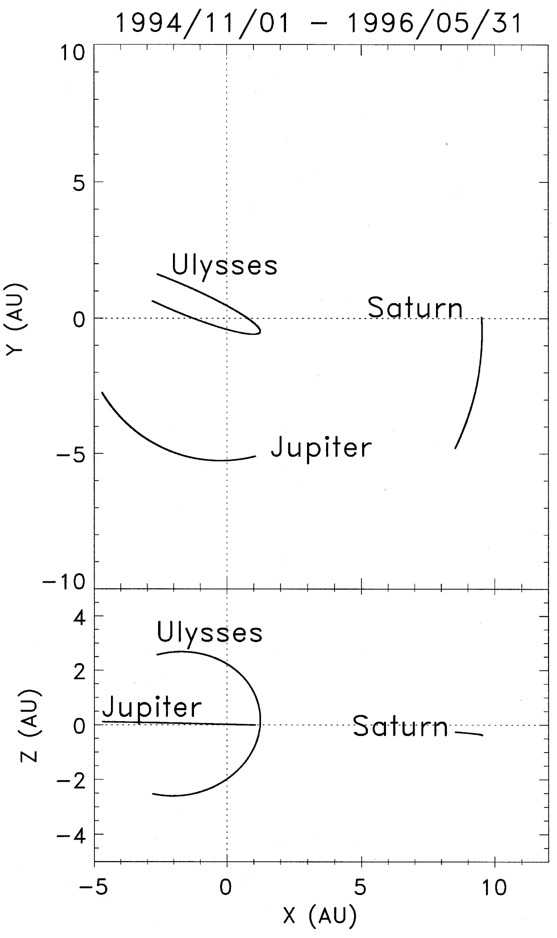

Figure 2: Positions of Ulysses, Jupiter and Saturn relative to the ecliptic.

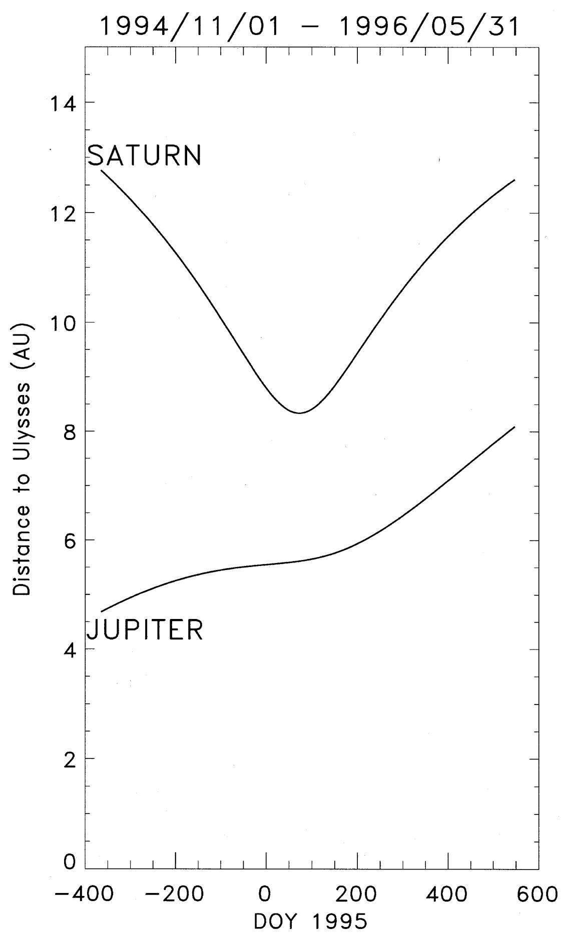

Figure 3: Ranges from Ulysses to Jupiter and Saturn.

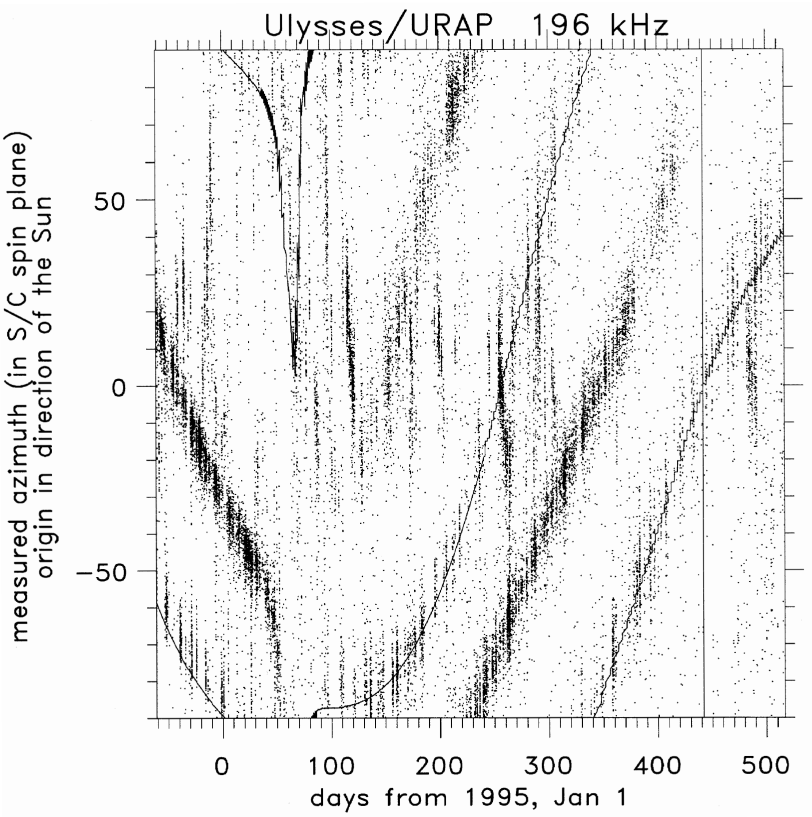

Figure 4: Measured azimuth of the detected events as a function of time. The line displays the ephemeris position of Saturn, well in agreement with one drifting cluster of points. Other clusters correspond to Jovian emissions and solar type III storms.

Figure 4 illustrates the efficiency of the detection/classification method described in the previous section. Each dot corresponds to a 12s sample (at 196 kHz) for which significant activity was detected and the azimuth in the antenna reference frame could be measured: all dots aggregate in disjoint clusters of points, aligned with the ephemeris positions of Jupiter, Saturn or the Sun. In case of the Sun, the reference azimuth is 0°, but solar type III bursts may originate at some distance from the Sun.

When looking at the occurrence of SKR in function of the frequency, one finds that the observed occurrence increases from 52 kHz channel up to the 196 kHz channel, gets a maximum between 196 and 272 kHz and then decreases and becomes very low above 540 kHz. This behaviour corresponds to the shape of the SKR spectrum as observed by *Voyager*/PRA, but with an additional "blockage by the galaxy", whose brightness suddenly increases above 400 kHz and lowers the *Ulysses*/URAP detection capability.

The SKR polarisation is also in agreement with the observations and interpretations from *Voyager*/PRA [Ortega- Molina and Lecacheux, 1990]. On *Ulysses* data, the SKR polarisation oscillates between 100% left-handed and 100% right handed circular polarisation, as expected from the simultaneous observations of rapidly fluctuating emissions from both northern and southern hemispheres. As expected also, the proportion of left-handed sense, with respect to the right handed sense, was observed to reverse when *Ulysses* crossed the Saturnian ring plane in mid-1995.

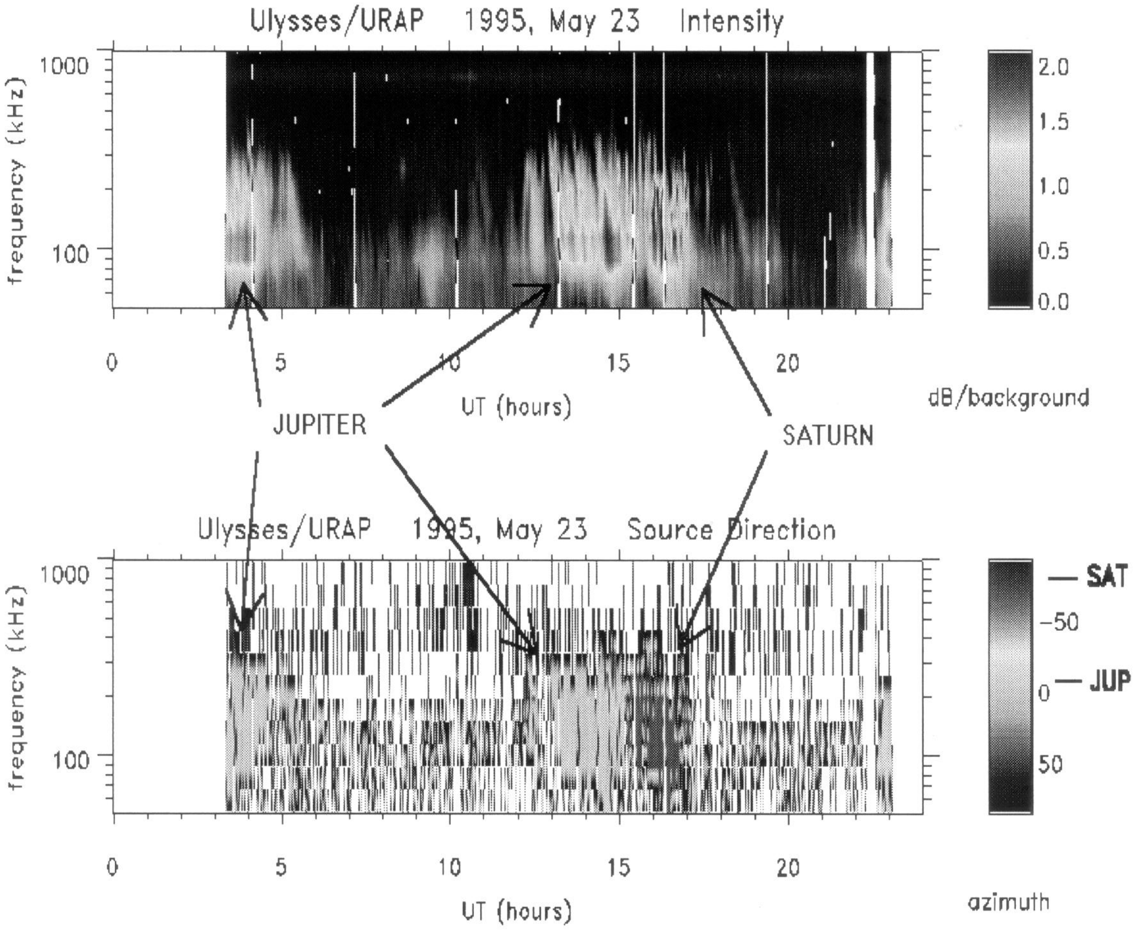

Figure 5: Example of SKR observation. The upper panel is a conventional dynamic spectrum with the color bar corresponding to the recorded emission intensity. In the lower panel, the direction of the source is color coded instead.

Figure 5 is an example of SKR dynamic spectrum observed in mid 1995 by *Ulysses*/URAP. As recorded by Voyager/PRA, the SKR dynamic spectrum is highly structured, with drifting spectral features within a broad envelope; as shown in the example, the SKR dynamic spectrum very much resembles that of Jupiter observed from high jovigraphic latitudes.

Figure 6 shows, for the entire period, the histogram of the recorded SKR flux densities, normalised to 1 AU. The frequency used in the figure is 196 kHz. All the studied frequencies show the same result: the SKR average flux density appears to be about one order of magnitude larger on *Ulysses* then previously quoted from *Voyager* data [Kaiser et al., 1981; Kaiser et al., 1984]. This is quite surprising since, as remarked above, the viewing geometries from Saturn are very similar for both spacecraft. Therefore, secular variations of the SKR may exist, maybe linked with the solar cycle or the position of Saturn on its orbit. Another explanation could come from the intrinsic burstiness of the SKR radiation: indeed, the *Voyager* flux measurements were obtained from original PRA data, log-averaged over 48 seconds, while the *Ulysses*/URAP measurements are linear intensity averages, over only 12 seconds.

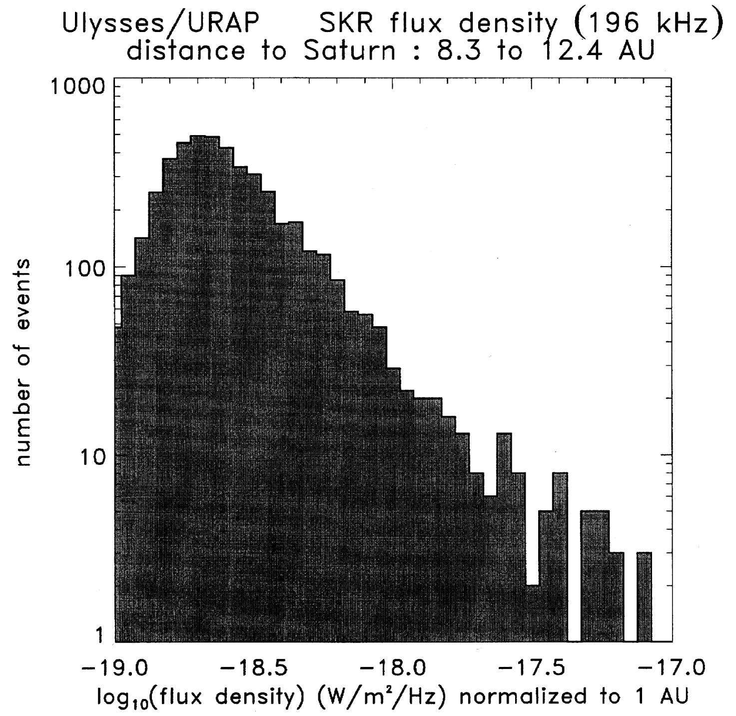

Figure 6: Histogram of the recorded SKR flux densities, normalized to 1 astronomical unit.

5 Evidence for solar wind control

Evidence of direct control of the solar wind on SKR was provided by Desch [1982]. He showed that the ram pressure or some associated property is the most important solar wind parameter in controlling the intensity level of Saturn's radio emission. As stated by Desch and Rucker [1983], "solar wind ram pressure is the primary driver of Saturn's radioenergy output". They found linear correlation coefficients of about 0.6 between the SKR level and the ram pressure for both Voyager 1 and 2. Desch and Rucker [1983] examined 13 solar wind quantities and showed that large-amplitude fluctuations of the SKR emission are best correlated with the solar wind ram pressure variations. Furthermore, the fact that, during the Voyager 2 encounter, a total disappearance of the SKR for about 2 days was observed, coinciding with a possible immersion of Saturn in Jupiter's magnetic tail or tail filament [Kurth et al., 1983], appears to be an expected response of Saturn's magnetosphere shielded from the direct solar wind interaction.

In the purpose to check for solar wind control of the SKR from the Ulysses data, we studied the correlation between the SKR activity observed by Ulysses and measurements of the solar wind parameters at the Earth, available from satellites. A more rigorous correlation study would require a model of the solar wind able to project the properties measured from the Earth up to Saturn. Here we do not appeal for such a model.

The top panel of Figure 7 displays the ram pressure of the solar wind (i.e. proton mass density times bulk speed squared) measured at the Earth orbit (data extracted from NSSDC archives). Its magnitude varies typically from 1 to 15 nPa, and should correspond to $1-200$ pPa at Saturn. The time period used for the analysis extends from October 28,

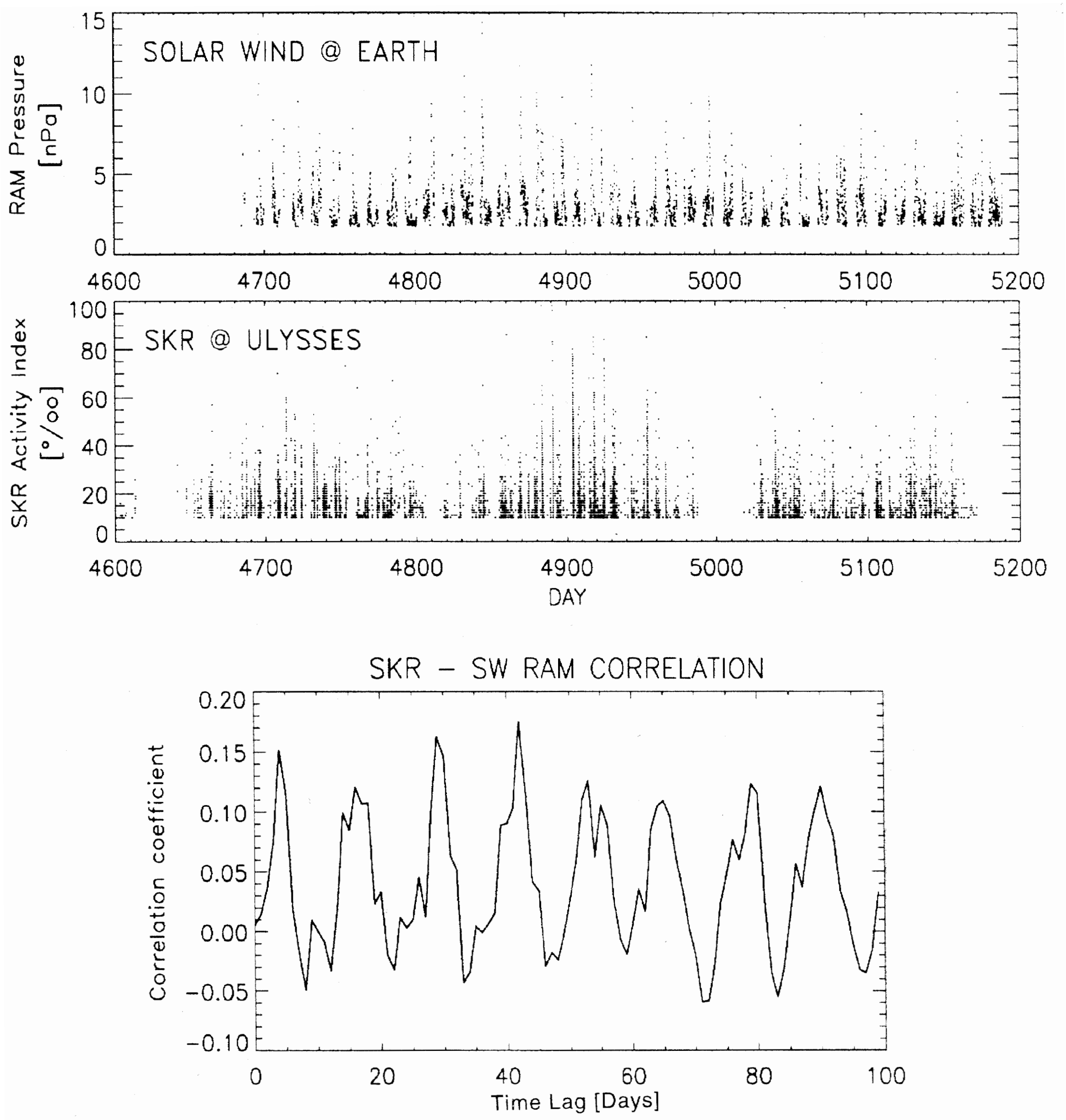

Figure 7: Analysis of the correlation between the SKR activity and the solar wind observed at the Earth.

1994 (day 4683, day 1 starts Jan 1, 1982, 00:00 UT) to March 17, 1996 (day 5189) and the time resolution is 1 hour. In order to reduce the noise in the correlation, we have selected data the magnitude of which is greater than the most frequent value (hereafter called "solar wind events"). A modulation of this ram pressure at $\sim$ 13 days clearly appears due to the presence of a two-sector structure in the solar wind data at the Earth.

The middle panel displays for the same period of time the modulation index (in $^\circ$/oo) of the signal received by Ulysses, which we believe to be a significant parameter of the SKR activity. Here too, we have again selected the data greater than the most frequent value (hereafter called "SKR events").

The bottom panel of Figure 7 shows the result of cross correlating the number of SKR events during 24 hours with the number of solar wind events, for the same duration, for time lags from 0 through 100 days. A statistically significant linear correlation occurs for lags integral multiples of $\sim$ 13 days plus a delay corresponding to the flow of the solar wind between the Earth and Saturn. This result confirms the existence of the control effect by the solar wind, from the Ulysses data. In the general context of planetary radiations, Saturn appears then rather different from Jupiter whose radio emissions are mainly modulated by the planetary rotation and Io's motion and very low correlated with the solar wind [Carr et al., 1983]. These observations demonstrate the attractive potentiality, from a simple monitoring of the SKR activity - for example from Earth orbit -, to remotely and continuously survey the solar wind activity at Saturn's distance, i.e. as far as 10 AU from the Sun.

6 Rotation period

Saturn's radio period determination has been performed first by Desch and Kaiser [1981]. The analysis has been made on 267 days (i.e. about 600 rotations of Saturn) through the Voyager 1 data from the Planetary Radio Astronomy experiment. The authors used the same method which permitted to precisely define the System III rotation period of Jupiter: a spectral analysis applicable to unequally spaced data samples followed by a least squares fit in order to refine the obtained period. The result is a clear determination of the radio period of Saturn at 10h39m24 $\pm$ 7s (or 10.657 hr). Note that a second, less significant line appears in their power spectral analysis (see Figure 1 of Desch and Kaiser, [1981]) on the low frequency shoulder of the spectral main peak; it corresponds to a longer

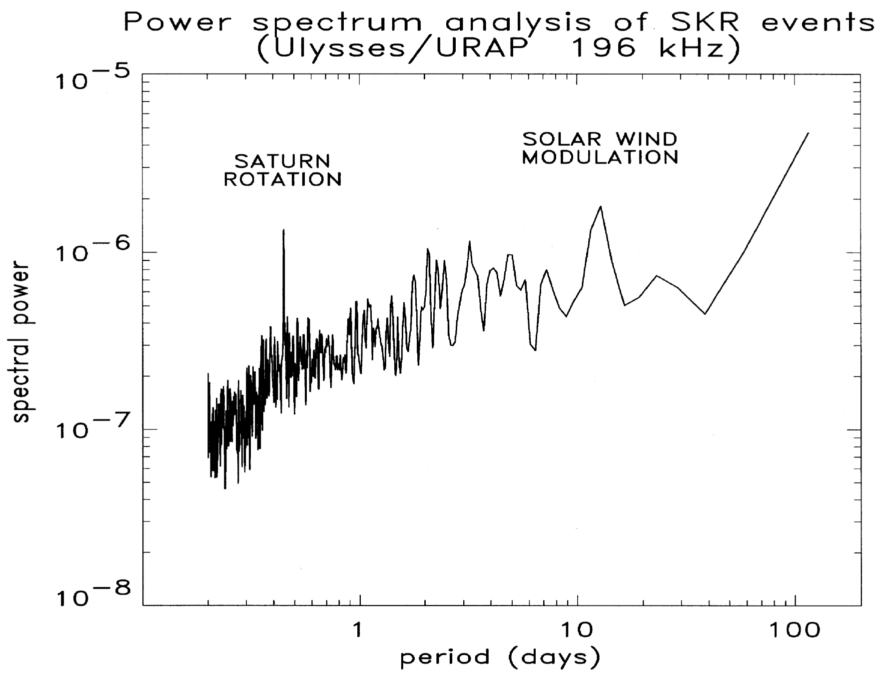

Figure 8: Low resolution, power spectrum analysis of the SKR emission time series at 196 kHz. The Saturn rotation (0.44 days) and the solar wind modulation period (13 days) are well visible.

period of 10.69 hr and was attributed to the contribution of a low intensity component of the SKR which reappears at a different, slightly longer period than that of the main component. However, by analogy with Jupiter, Desch and Kaiser proposed the adoption of a Saturn longitude reference system (SLS), by identifying the SKR radio period with the sidereal rotation period of Saturn.

A subsequent analysis of Voyager pre-encounter data has been done by Carr et al. [1981] during two periods around March and October 1980. By cross-correlation analysis of the flux density histograms recorded at various frequencies in function of the central meridian longitude (in the SLS longitude system), they deduced a period slightly shorter than the SLS one, but still in the error bar, i.e. 10h39m22s.

A direct measure of the Saturn rotation period was derived by Godfrey [1990], independently of the radio observations. He used a sequence of images (mainly taken by Voyager 2) of a particular cloud feature of the atmosphere of Saturn, a very high latitude belt, hexagonal in shape, thought to be a direct manifestation of the rotation of the deep interior of the planet. By using the 271 days distance between the Voyager 2 sequence (10 days long) and one isolated image from Voyager 1, he deduced a precise value (10h39m22s) of the rotation period of the cloud feature, identical to the radio period, and thus provided a strong indication that both such atmospheric features and radio emissions are linked with the interior of the planet.

Figure 8 displays the low resolution power spectrum of a time series, built from the SKR activity detected by *Ulysses* along the 578 days period ranging from Nov. 1, 1994 to

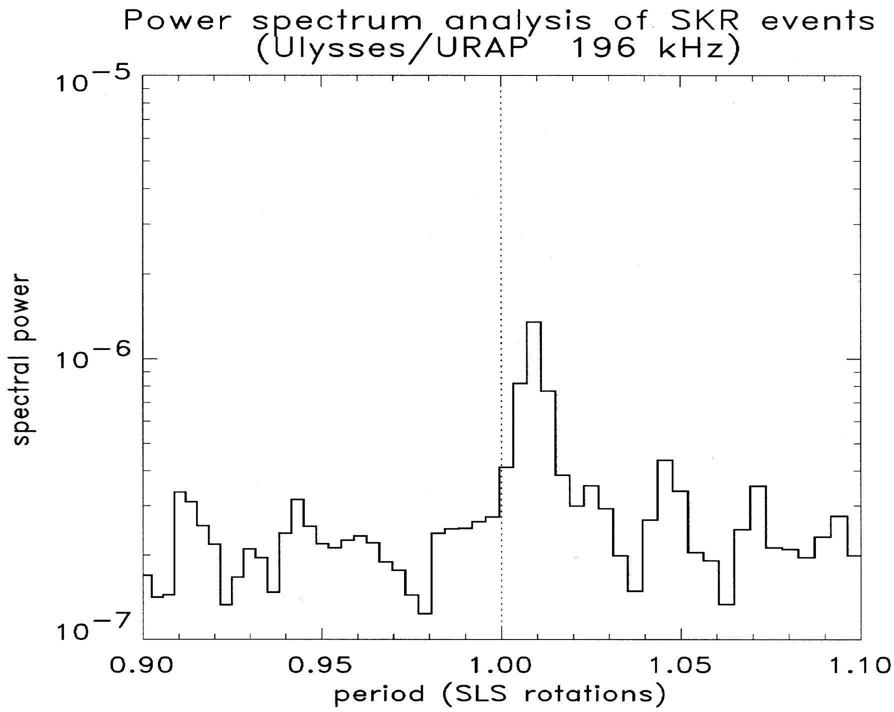

Figure 9: High resolution, power spectrum analysis of the SKR activity time series at 196 kHz. The period is normalized to the SLS period (10h39m24s) deduced from the Voyager observations.

May 31, 1996. The particular 196 kHz frequency channel is displayed, but other frequency channels get identical results. With a data span more than twice as long as the Voyager one, the plot confirms that only two periodicities control the SKR: the rotation rate of the planet (0.44 days) and the solar wind variations (about 13 days).

Figure 9 is a zoom of Figure 8 around the location of the power spectrum line at 0.44 days, after normalisation of the period axis to the SLS period. Quite surprisingly, it shows that the Saturn radio period is no longer consistent with the SLS period: we rather find a well defined period of about 10.76 hr, i.e. 1% longer than the SLS value. We have checked that the result was maintained, whatever the URAP frequency (from 52 to 487 kHz where SKR is well detectable) or the epoch of the utilised data set (for example by doing the calculation for five consecutive, independent 100 days time intervals). Moreover, by constructing histograms of SKR occurrence as a function of the rotation phase in a given longitude system, it was also checked that the use of SLS smeared out the data, when SLS+1% provide a well better shaped profile. It is worth noticing that aberration time and respective motion of Ulysses in Saturnian reference frame lead to negligible effects (less than 10^{-4} of SLS period) that we have not taken into account in this preliminary study.

This intriguing result has certainly to be confirmed by using more available *Ulysses* data. If it was found to be exact, the triggering and generation mechanisms of SKR should be re-examined, as well as the commonly agreed identification of radio periods of the planets with their sidereal rotation period.

7 Summary and Conclusion

The observations, related in this work, demonstrate that useful studies of the intense, auroral planetary radiations can be done with adequate radio astronomy instrumentation aboard spacecraft, even if the spacecraft orbit remains at very large distance from the observed planet. The URAP instrument, aboard the European spacecraft *Ulysses*, in high inclination orbit around the Sun, has all the needed qualities: sensitive receiver, long wire dipolar antennas, direction finding and polarisation analysis capabilities, RFI clean electrical environment.

New observations of the Saturn Kilometric Radiation, obtained during one and half years (Nov. 1, 1994 to May 31, 1995), were analysed in terms of average flux, spectrum, periodicities, polarisation, etc. and compared with previous *Voyager* results.

Most of the known properties of the SKR were retrieved. However, two major differences are found: the SKR average power flux appears ten times higher on *Ulysses* than on *Voyager*. The 10.7 hr occurrence period of the SKR is found to be 1% longer than the one deduced from the *Voyager* data.

The strong relationship between SKR intensity and solar wind ram pressure at Saturn, is well characterised: this might provide an efficient method for monitoring the solar wind variations at 10 AU, from an observatory in the neighbouring of the Earth.