PRODUCTION OF LONG TERM SKR TIME SERIES (AND DYNAMIC SPECTRA) WITH CASSINI – RPWS – HFR

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DRAFT – NOT TO BE DISCLOSED

This paper refers to several RPWS-HFR/Kronos products accessible via http://www.lesia.obspm.fr/kronos/ (username=rpwsTeam and password).

1. INTRODUCTION:

1) Final product:

The procedure of production of SKR series allows to create processed long term (time,frequency) arrays of intensities.

Different kind of intensities are obtained :

- flux density in $W.m^{-2}.Hz^{-1}$
- normalized flux density at 1 AU in $W.m^{-1}.Hz^{-1}$
-
- emitted powers in W.

2) Selection parameters :

General parameters as the time period, the time step and the frequency ramp define final arrays.

Moreover, physical selections on data thanks to specific parameters are allowed. Using n3e (level '3e') data, user defines a range of circular polarization (V) and a range of angles (azimuth θ, colatitude φ) of the emission arrival direction.

2. DATA :

Hereafter are specifed and discussed data on which our procedure is based on.

1) Choice of data :

a) Physical parameters extracted from direct inversions:

The Cassini spacecraft (S/C) is able to perform 2 (or 3) antennas measurements. Corresponding calibrated auto- and cross-correlations are stored in n2 ('level 2') data (see below). Analytic Direct Inversions (DI) applied on n2 data retrieve 4 (or 6 respectively) of 6 physical parameters between :

- the **4 Stokes parameters** (S, Q, U, V)
- the **2 Direction Finding (DF) parameters** (azimuth θ and colatitude φ) of the signal arrival direction

Results of DI are stored in n3 (level '3') data (see below). Note that DI are physical only if they concern electromagnetic propagating waves.

b) Choice of 2 antennas measurements :

Since 3 antennas measurements are quite rare compared to 2 antennas measurements that work quasi-continuously, 2 antenna measurements will preferentially be used for long-term series production.

According to the observing situation of the S/C, a physical hypothesis postulates 2 of the 6 unknown parameters. DI applied to 2 antenna measurements are then able to retrieve the 4 other parameters.

c) Basis hypothesis and corresponding data level :

Before the encounter, Cassini could considered Saturn as a point source : DF coordinates (θ,φ) were fixed to Saturn position and « polarimetric » DI extracted intensity (S), normalized circular polarization (V) and normalized linear polarization parameters (U, Q) stored in n3d (level 'n3d) data.

Since the S/C reached Saturn in July 2004, the source can be considered as extended and DF parameters (θ,φ) cannot any more remain fixed at Saturn position. However, *Cecconi (et al , 2005)* showed thanks to previous Cassini results than SKR linear polarization (U, Q parameters) can be neglected. Based on the hypothesis : **U = Q = 0** , resulting « goniometric » DI extracts intensity (S), normalized circular polarization (V) and DF coordinates (θ,φ), stored in n3e (level 'n3e) data on which the procedure will be based on.

2) RPWS-HFR/KRONOS data :

As detailed further, not only n3e but n2 and n3d data are required. These products are recalled below (for more precision, see description in *Cassini-RPWS-HFR/KRONOS Data in Meudon, Zarka et al*). Useful parameters are bold.

a) n2 products :

n2 data are calibrated values of auto- and cross-correlations of antenna.

n2 data provide :
- **t97 : time (decimal days, epoch = 1997.0)**
- **f : frequency**
- dt : effective integration time (msec)
- df : effective bandwith (kHz)
- autoX : auto-correlation 'X' (V^2Hz^{-1})
- autoZ : auto-correlation 'Z' (V^2Hz^{-1})
- crossR : cross-correlation (real)
- crossI : cross-correlation (imaginary)
- ant : antenna selection : 0-3=No Direction Finding (DF)

b) n3d products / Polarimetry :

n3d data are polarization (V,U,Q) results from Direct Inversion (DI) method applied to 2 antenna measurements with preset source direction (θ, φ fixed) (*cf. Cecconi & Zarka, 2004*).

n3d data provide :

- S : Intensity ($V^2m^{-2}Hz^{-1}$)
- **V : Normalized circular polarization (further V^{n3d})**
- U : Normalized linear polarization parameter
- Q : Idem
- θ : Source colatitude (in S/C frame)
- φ : Source azimuth (in S/C frame)
- SN : S/N ratio on autocorrelated values

c) n3e products / Direction Finding:

n3e data are DF (θ, φ) / polarization (V) results from DI method applied to 2 antenna measurements with U = Q = 0 (*cf. Cecconi & Zarka, 2004*).

n3e data provide :

- **S : Intensity ($V^2m^{-2}Hz^{-1}$)**
- **V : Normalized circular polarization (further V^{n3e})**
- U : Normalized linear polarization parameter
- Q : Idem
- **θ : Source colatitude (in S/C frame)**
- **φ : Source azimuth (in S/C frame)**
- SN : S/N ratio on autocorrelated values

3. INDEXATION OF DATA:

Before to produce long-term intensity series, a preliminary selection process has in charge to index data thanks to physical criteria.

1) Selection Criteria:

a) SNR min :

S/N ratio is mainly responsible of the quality of data. Exclusion of weakest data depends on the led study. SNR min is per default set to :

SNR min = 0

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b) Circular polarization V^{n3e}:

Assuming the hypothesis U = Q = 0, n3e data are consistent only for purely circularly polarized electromagnetic emissions. As SKR represents the most part of emissions, V^{n3e} should allow to discriminate between two polarized components of SKR, left (V^{n3e} = +1) or right handed (V^{n3e} = -1) polarized emission.

However, observed values of $|V^{n3e}|$ cover a large range of polarizations (see Fig. X) .

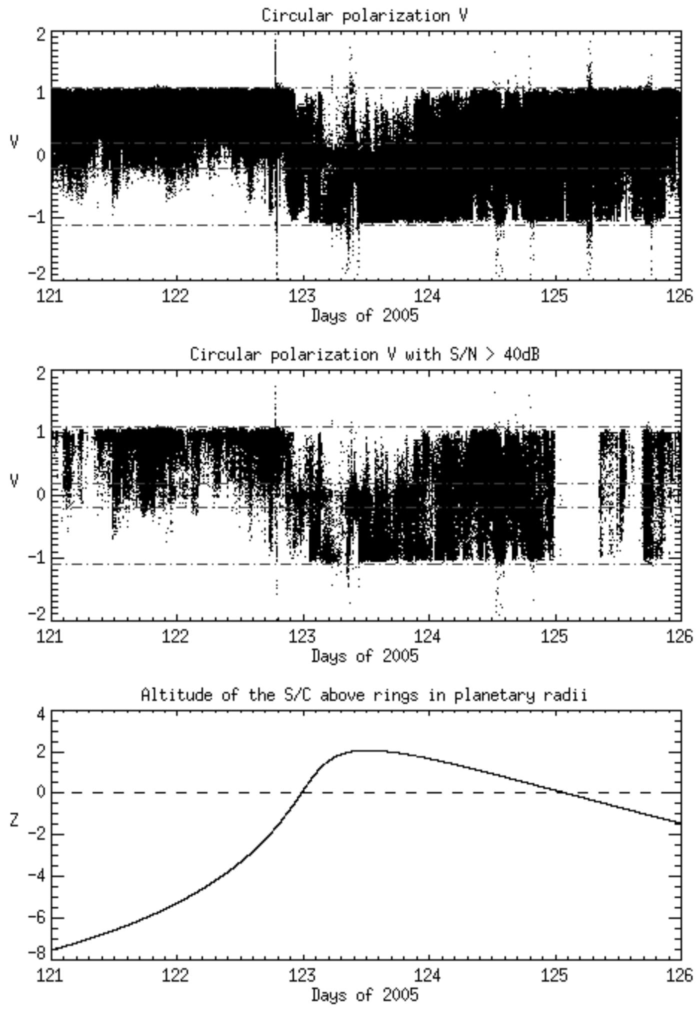

Fig. X : Views of circular polarization V with and without a selection on S/N ratio. In the southern hemisphere, emissions are left handed polarized component ($V^{n3e} \sim +1$*) while in the northern hemisphere, they are right handed polarized (*$V^{n3e} \sim -1$*)*

Concerning circularly polarized electromagnetic emissions, this is due to the precision on V^{n3e} that depends on :

- S/N ratio
- the angular distance from the source direction to the antenna plane $\beta_{\pm XZ}$

Typical error on the polarization in n3e (V^{n3e}) is about 0.1 (for more precision, see *Cecconi & Zarka, 2005*).

But several other types of emissions than SKR are observed by the S/C with corresponding extracted V^{n3e} values. We can distinguish some different cases:

- electromagnetic non polarized emissions (solar type III bursts) : added to U = Q = 0 , DI should give $V^{n3e} \sim 0$.
- electromagnetic non purely circularly polarized waves (jovian emissions) : hypothesis U = Q = 0 is wrong as values of V^{n3e}.
- non electromagnetic propagating emissions (electrostatic local emissions) : values of V^{n3e} are meaningless.

In conclusion, in order to select SKR polarized components (excluding [-0.1,0.1] V^{n3e} range and taking account of maximal error 0.1), two ranges of polarization are defined by :

$0.2 < |V^{n3e}| < 1.1$
RH : $V^{n3e} < 0$
LH : $V^{n3e} > 0$

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c) Circular polarization V^{n3d} :

In spite of selection on V^{n3e} which should remove most of the polluted signal, some frequency bands remain polluted by Radio Frequency Interferences (RFI). RFI pollution occurs especially at harmonics frequencies of a 100 kHz fundamental, which corresponds to the RPWS DC/DC converter frequency (see appendix 1).

To reduce the amount of polluted signal, we use an additional selection on n3d circular polarization V^{n3d} before the selection on V^{n3e}. Polluted franquency bands disappear on resulting dynamic spectra (see Fig. H). Consequent missings of the signal coming from the removal of polluted signal would be processed in a further stage.

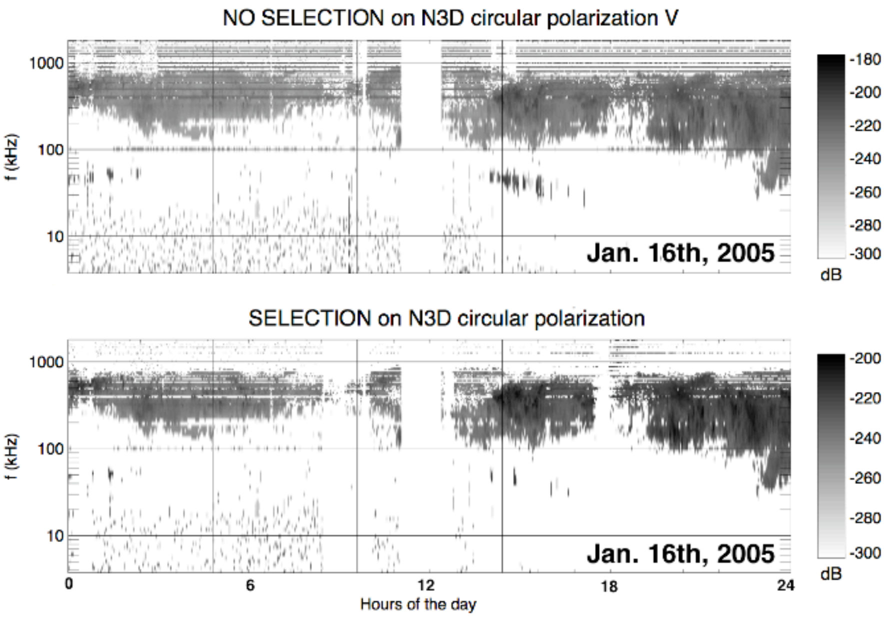

Fig. H: Two dynamic spectra of Jan. 16th, 2005. Top spectrum has been processed by a selection on V^{n3e} only (LH). Bottom spectrum has been processed by a selection on V^{n3e} and V^{n3d}.

The reason why V^{n3d} corresponding to polluted signal is more often out of range than V^{n3e} is not clear.

Complete selection on circular polarizations V^{n3e} and V^{n3d} is :

$0.2 < \lvert V^{n3e} \rvert < 1.1$ **RH : $V^{n3e} < 0$** **LH : $V^{n3e} > 0$**	and	**$0.2 < \lvert V^{n3d} \rvert < 1.1$** **RH : $V^{n3d} < 0$** **LH : $V^{n3d} > 0$**

d) Source location:

n3e data return not only S and V^{n3e} but DF coordinates (θ, φ). We propose to use such coordinates to define regions in the observation plane that allow to distinguish most of the signal from aberrant data (coming from radio frequency interferences etc…) or imprecise one (due to large errors on θ, φ etc…).

Like V^{n3e}, the precision of these informations about the source location depends on SNR and $\beta_{\pm XZ}$. Typical error on θ and φ in n3e is about 2° (see *Cecconi & Zarka, 2005*).

To discriminate between emissions coming from north and south hemispheres, a lower latitude of arrival direction is taken be equal to 2°.
Once in a hemisphere, we limit the zone where emission is expected at a radius of 2° above
A maximal angle corresponding to 10Rsat.

These limits are summarized below :

Minimal latitude (above rings) = 2° **Maximal latitude (above rings) = atan(10 Rsat / r) + 2°** *where r is the distance to Saturn in Rsat*

Thanks to these values, we define 5 different (θ, φ) zones (as shown in Fig. Y) :

- north and south regions (where emission is expected)
- center region (where imprecision is too high) and
- outer north and south zones that cover the rest of the distribution.

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2) Selection procedure :

Once selection criteria are defined, data are sorted by an indexation.

a) Indexation of data :

An index is attributed to each n3e data set (S,V^{n3e},θ, φ). This index refers to a combination of 3 different selections : on the S/N ratio, on the polarization state, on the location of the source. 11 index (from -1 to 10) are summarized in the table X and the Fig. Z. below :

Index	SNR	V^{n3e}	Region
0	< SNR min	No selection	No selection
1	> SNR min	RH	North
2	> SNR min	LH	North
3	> SNR min	RH	South
4	> SNR min	LH	South
5	> SNR min	RH	Center
6	> SNR min	LH	Center
7	> SNR min	RH	Outer north
8	> SNR min	LH	Outer north
9	> SNR min	RH	Outer south
10	> SNR min	LH	Outer south
-1	Rest of non indexed data		

Table X. : List of index used in the n3e data selection procedure. SNR min, RH, LH, and regions refer to definitions given in previous parts.

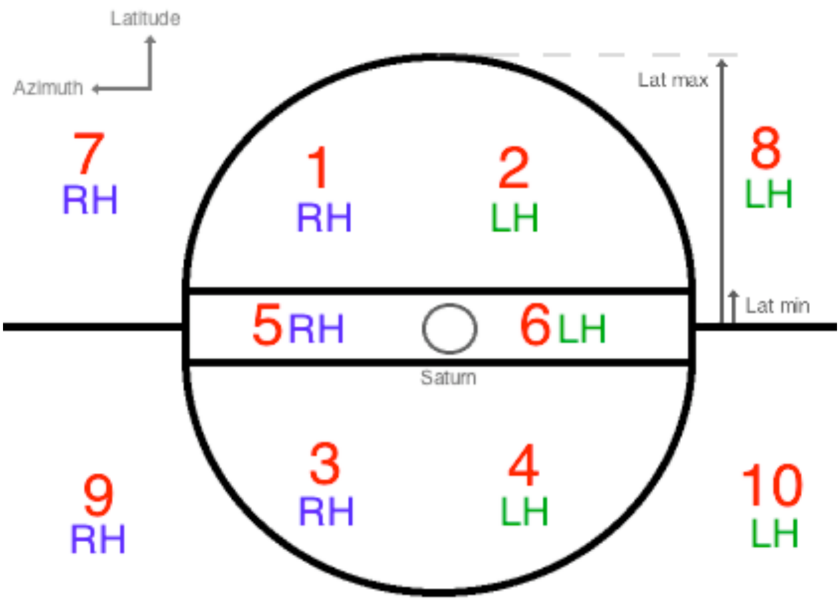

Fig. Z : Indexation of n3e data with selections on physical criteria. Angles Lat min (Lat max) corresponds to the minimal (maximal respectively) latitude.

b) Index files :

As each n3e data set (S,V^{n3e},θ, φ) is unique and defined in n3e data by num & ydh values (see part 2.), index files have the same size as n3e structures and index files are recorded in a /temp folder on the kronos server with the following structure :

```
Index = { ydh : 0L,   $        ; yyyydddhh of current files
           num : 0L,  $        ; Index of record in current file (for one-to-one correspondance
                                 with any level)
           ind : 0.,  $        ; Index value (from -1 to 10)
            tl : 0.,  $        ; Local Time
            rr : 0.,  $        ; Distance from the S/C to saturn (in kronian radii)
            zz : 0.,  $        ; Distance of the S/C above the rings plane (in kronian radii)
           ydf : 0.,  $        ; Orthogonal coordinates of the emission in the observation
           zdf : 0.}           ; plane (ydf  lying on the rings plane and zdf lying on the north)
```

Index files are hourly files.

4. STAGES OF DATA PROCESSING:

Final products are regular (time, frequency) arrays (i.e. dynamic spectra) of intensities computed from S^{n3e} (in V^2. Hz^{-1}):

- **averaged fluxes S** normalized at 1 AU (in W. Hz^{-1})
- **powers PWR** (in W)

Dimensions and thinness of final arrays are preliminary fixed by choosing:

- **Frequency ramp**
- **Time ramp** : recquires time step and dates of beginning/end of the period.

Before to fill final arrays, data are processed day per day and mode per mode in a day through several stages that are described below.

0) Selecting data :

Role of preliminary selection(s) is to select a chosen SKR sub-component thanks to index files (cf part 3.). A selection is defined by any combination of index from 0 to 10.
Ex : Index 1 selects RH SKR on north region with SNR > SNRmin.
Index 2, 4, 6, 8 and 10 select whole LH SKR with SNR > SNRmin.

1) Primary integration :

First, primary (time, frequency) arrays are created. As final arrays, dimensions and thinness of arrays are preliminary fixed by defining:

- **Frequency ramp :** thanks to n2.f data, a systematic ramp containing all HFR frequencies of the current mode is generated (further called « real frequencies »).
- **Time ramp :** in order to obtain a primary time ramp as thin as possible, we should take into account the maximal sweeping time of ABC, H1 and H2 frequency bands. Following Zarka & al, 2004 (see Fig B.), primary time step is taken equal to :

Dsec1 = 180s

Second, arrays are filled pixel per pixel with corresponding S/PWR intensities. A pixel defined by its coordinates (t±Δt,f±Δf) is filled with **arithmetic average** of intensity : in time and frequency for fluxes but only in time for powers. If there is no data corresponding to one pixel, its value is set **to the default unphysical -1 value**.

Fluxes S (in $W.m^{-2}.Hz^{-1}$) are calculated from fluxes S^{n3e} (in $V^2. Hz^{-1}$).

$$S = S^{n3e}/(Z_0*L^2*Ca^2/(Ca+Cb)^2)$$

where : *(cf Zarka et al, 2004)*

- Z_0 : is the impedance of free space ~ **377ohm**
- L : is the effective length of the monopole Z **~1.68m**
- Ca : is the antenna capacitance ~ **100pF**
- Cb : is the base capacitance **~150pF**

Fluxes PWR (in $W.m^{-2}$) are calculated from S (in $W.m^{-2}.Hz^{-1}$).

$$PWR = S*\Delta f$$

where Δf corresponds to the spectral bandwidth associated to the real frequency ramp.

2) Reducing of data:

Fluxes arrays correspond to dynamic spectr a. A cleaning processing is applied separately **on each frequency spectrum.** Isolated pixels are excluded and resulting spectra are interpolated to rebuild missing parts of signal.

a) Removal of isolated pixels :

An isolated pixel is defined as a positive intensity value (≥ 0) flanked with two -1 values (cf first integration). When isolated pixels are detected, their value **is set to 0**.
On the pannel (b) of the fig. Z, an isolated pixel is detected and removed at the right side of the spectrum.

b) Interpolation :

Aim of spectra interpolation is to rebuild missing parts of signal that have been excluded by preliminary selection and result in -1 default values in primary arrays of intensity (cf primary integration).

Interpolation is processed on -1 default values when following condition is verified : **number of consecutive -1 default values should not overcome 4 pixels.** This limit has been chosen by observing the characteristic width of RFI bands (see Apprendix 3).

When condition is verified, default -1 values are lineraly interpolated between closest positive (≥ 0) intensities of initial spectrum. On the pannel (c) of the fig Z, we observe that condition of interpolation is verified (and interpolation applied) only on 3 holes for a total of 6.

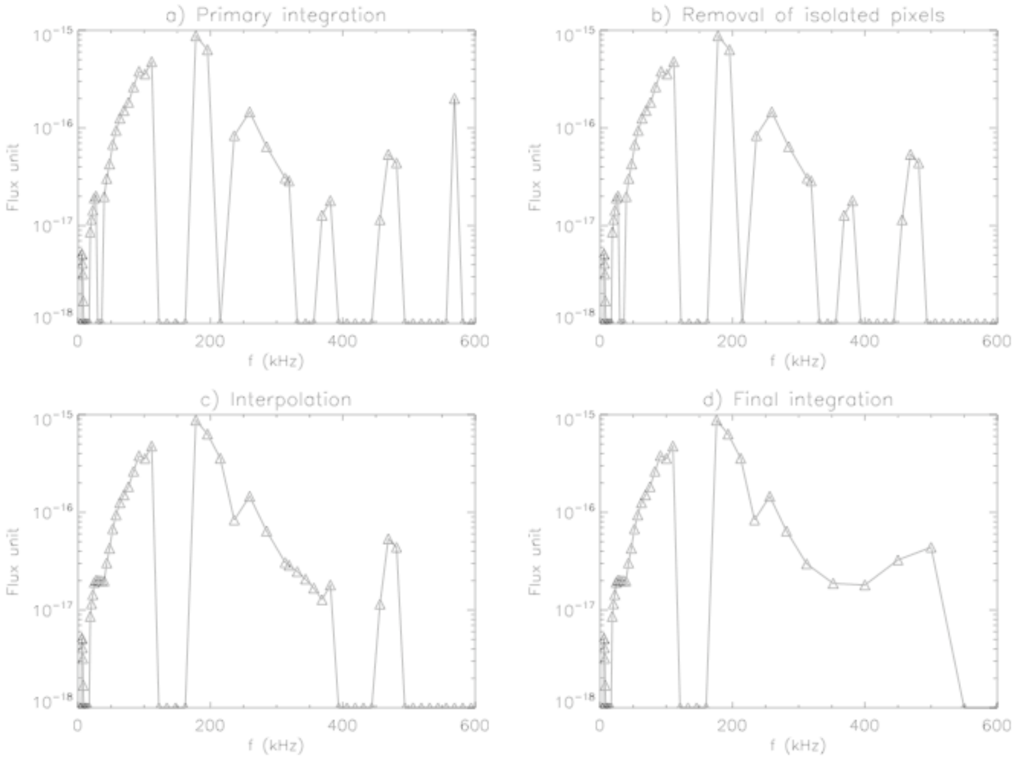

Fig Z. : Example of processing of a S frequency spectrum of the day 2005_040 with selection of LH polarized signal (SNRmin=0). Default -1 values have been set to 10^{-18} to facilitate plots and frequency range is restricted to [0,600kHz]. Pannel (a) gives a frequency spectrum created in the first integration. Pannel (b) illustrates the removal of an isolated pixel located at the right side of the first spectrum. Pannel (c) shows how signal is interpolated when successive -1 default values do not overcome 4 values. Finally, pannel (d) shows the final spectrum with the final frequency ramp (less thin than real frequency ramp in H1 band).

3) **Final integration :** S/PWR/V[n3e]

Cleaned updated S/PWR intensity arrays are transposed in final regular (time, frequency) arrays. If primary arrays are thinner than final one, values are arithmetically averaged in correspondings pixels (cf pannel (d) of the fig Z).

As in primary integration, time and frequency ramps have to be defined. The choice of a time step and a frequency ramp depends of the led study.

For instance, to study SKR period, we have chosen a relatively coarse frequency ramp defined by :

- ABC Bands : 8 channels/band = 24 frequencies with a precision Δf/f = 10%
- H1 Band : 1 channel/band every 50kHz = 24 frequencies between 325 and 1500kHz

and a final time step of 180s.

4) Concluding stage :

Once final S/PWR arrays are obtained, fluxes are inverse-square corrected from the distance to Saturn.

Fluxes S can be normalized at 1 AU PWR (in $W.Hz^{-1}$):

$$\mathbf{S = S^{*}r_{ua}^{2}}$$

where r_{au} is the distance to Saturn in astronomical units.

Fluxes PWR (in $W.m^{-2}$) can be corrected to give powers :

$$\mathbf{PWR = PWR^{*}r^{2}}$$

where r is the distance to Saturn in m.

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APPENDICES

Appendix 1 : Histogram of counts number vs frequency for 2004, days 115 to 141

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