SURA-WAVES experiments: calibration of the Cassini/RPWS/HFR instrumentation

Abstract

The SURA facility transmitted signals in the 9 MHz frequency range to the Cassini spacecraft during the Earth flyby on August 18–23, 1999. Before reaching Cassini the emission was also observed by the WIND/RAD2 receiver, which had already been calibrated with similar former observational campaigns. The SURA signals recorded by both spacecraft are well above the background noise. We use these joint measurements to calibrate the Radio and Plasma Wave Science, High Frequency Receiver (Cassini/RPWS/HFR) in its monopole mode. An estimation of the conversion coefficient that links the measured signal in V^2/Hz to the incoming flux density in $Wm^{-2}Hz^{-1}$ near the main antenna resonance is conducted. A possibility to calibrate a radio receiver on board a spacecraft using cooperative simultaneous observations of solar type III emission by the WAVES instrument is pointed out.

1 Introduction

Investigations of the near-Earth space environment by observation of the SURA facility signals (4.6–9.3 MHz) aboard the WIND spacecraft using WAVES/RAD2 receiver have been successfully conducted since August 1995 [Klooster et al., 1995]. The same experiment was conducted again in August 1999 during Earth flyby of the Cassini spacecraft [Kurth et al., 2001]. The RPWS/HFR instrument covers the SURA operating frequency range. Seven sessions of SURA transmissions were carried out to calibrate the HFR instrument. We are studying here the first of these sessions which occurred on August 18–19, 1999. During this session the WIND and Cassini spacecraft were both positioned in the main beam of the SURA antenna pattern nearly simultaneously. The results of this experiment are discussed in this paper. We are primarily concerned with the HFR autocorrelations keeping the cross-correlation properties analysis for a future paper.

2 Instrumentation

2.1 SURA Facility

The SURA transmitting facility (56° N, 46° E) consists of three powerful transmitters 250 kW each and a 144–dipole antenna array with 300 by 300 m^2 area covering the frequency range 4.6–9.3 MHz [Karashtin et al, 1999]. The antenna beam can be steered in the local magnetic meridian plane with azimuth $A = 9°$. For a vertical orientation, the half-power beam width of the full antenna array is 6.3° by 6.3°, the angular size of the inclined beam changes in the elevation plane proportionally to $\sin(z)$, with z being the zenith angle; for the sub-module regime (one transmitter connected to identical 48 dipole antenna sections) the elevation beam width is trebled. Circularly polarized waves can be radiated in either the O or X mode.

2.2 WIND/WAVES/RAD2 Receiver

The WAVES instrument provides measurement of the radio and plasma wave phenomena which occur in Geospace [Bougeret et al, 1995]. We have used the WAVES/RAD2 receiver (operating frequency range: 1075–13825 kHz) connected to two orthogonal dipole antennas. The Z-antenna 2×5.3m long is aligned with the spacecraft's spin axis pointed to the ecliptic pole. The Y-antenna 2×7.5m long rotates in the ecliptic plane (one turn per 3 sec). The RAD2 receiver was calibrated using the galactic background radiation [Dulk et al, 2001]. During the experiment, the RAD2 receiver was operating in a fixed frequency mode (9025 kHz) with a 16 Hz sampling rate and an half power frequency bandwidth (HPBW) of the order of 20 kHz. The RAD2 receiver was operating in a mode such that the signals from the Y and Z-antennas are measured separately.

2.3 Cassini High-Frequency Receiver (HFR)

The main goal of the RPWS experiment onboard Cassini is to investigate Saturn and its environment. We are using data from the High-Frequency Receiver (HFR), which consists of a pair of identical receivers analyzing the radio waves in the 3.5–16125 kHz frequency range, which covers the SURA operating frequencies. The receivers can be connected to two of the three RPWS electric antennas which are 10-m monopoles referred as u, v and w [Gurnett et al, 2004]. The u and w antennas as well as v and w ones are almost orthogonal to each other. The angle between the u and v antennas is about 120° [Vogl et al, 2004]. During the studied period of time the HFR was in its direction-finding (DF) mode, i.e. switching alternatively between the (u, w) and the (v, w) pairs of electric monopoles. The instrumental set up for the 4025 to 16025 kHz frequency band was the following: 200 kHz frequency steps, 25 kHz frequency bandwidth and 32 sec sampling rate (i.e. 1 frequency sweep per 32 sec). This operating mode provides quasi-simultaneous measurements of complex voltage autocorrelations and cross-correlations for each pair of antennas. The angles between the Cassini–Earth line and u, v, w antenna axes were 96°, 48° and 141° respectively. As the antennas are 10-m long, the SURA emission frequency range is close to the electrical resonance.

3 Calibration procedure

The aim of this study is to obtain the conversion coefficient (K) between the measured signal autocorrelations (A) and the real incoming flux density (S):

$$A = K \times S \tag{1}$$

with A in $\mathrm{V^2Hz^{-1}}$, S in $\mathrm{Wm^{-2}Hz^{-1}}$ and K in $\Omega\mathrm{m}^2$. The K coefficient is the receiver gain, including the antenna system impedance.

In order to compute the K value, it is necessary to observe a radio emission with a known absolute value of flux. Zarka et al. [2004] used for Cassini/RPWS/HFR the cosmic radio background with flux density S_b [Dulk et al., 2001] for such a source. In the paper we will derive an independent estimate of K based on the SURA signal and a solar type III burst observations on Aug 18–19, 1999. The absolute value of the incoming flux density is provided here by the WIND/WAVES/RAD2 instrument, which has been calibrated in a former experiment.

Using Eq. (1) for both receivers, it then easy to write the RPWS/HFR receiver gain K_C:

$$K_C = K_W \times (A_C/A_W) \times (S_W/S_C) \tag{2}$$

where the C and W subscripts are referring to the Cassini and WIND spacecrafts respectively. This equation can then be used to calibrate the Cassini/RPWS/HFR receiver using calibrated WAVES/RAD2 data.

Each of the two calibrations (solar type III bursts or SURA emission) procedure are slightly different: in the case of solar bursts observations the incoming flux density is the same for both receivers ($S_C = S_W$); in case of the ground-based transmitter the incoming flux density is inversely proportional to squared distance from the Earth D. We suppose here that the waves are propagating through Earth's magnetotail without any absorption. We must also keep in mind that the frequency band of SURA emission fluctuations is much less than each receiver's bandwidth. For such narrow-band emission the effective flux density is inversely proportional to the receiver bandwidth δf (The effective flux density of radio source with narrow-band emission spectrum is flux density of such radio source with wideband (noise-like) spectrum, which can produce the equal receiver's reply).

These considerations imply that Eq. (2) rewrites as:

$$K_C = K_W \times (A_C/A_W) \times \begin{cases} 1 & \text{solar type III burst} \\ (D_C/D_W)^2 \times \delta f_C/\delta f_W & \text{SURA emission} \end{cases} \tag{3}$$

where D_W, D_C are spacecraft distances from the Earth; δf_W, δf_C are receiver bandwidths respectively. At time of the experiment the announced values of receiver's bandwidth were almost the same for both instrument: $\delta f_W = 20\mathrm{kHz}$, $\delta f_C = 25\mathrm{kHz}$ (see 2.2, 2.3 Sections). The expected value of $\delta f_W/\delta f_C$ factor is then 1.25.

The conversion coefficient K_W for WAVES RAD2 receiver used in the following numerical computations is:

$$K_W = 4.1 \times 10^2 \, \Omega\mathrm{m}^2 \tag{4}$$

This value was obtained from Eq. (1) with previous determination of the cosmic background level $A_b = 3.4 \times 10^{-17}\,\mathrm{V}^2/\mathrm{Hz}$ for Z-antenna output of RAD2 receiver, based on the space noise observations in quiet period for WIND location far from Earth, and with the flux density of the cosmic background for dipole antenna $S_b = 8.3 \times 10^{-20}\,\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$ at 9 MHz [Dulk et al., 2001]. Relative accuracy of the estimation is about ±10%, absolute accuracy depends on present accuracy of the cosmic background radio spectrum determination (about ±30% in the 9 MHz frequency range) [Cane, 1979].

In order to compare the data sets recorded on two different receivers (WAVES/RAD2 and RPWS/HFR) it is convenient (mainly for illustrative purpose) to use the signal-to-background ratio $R = A/A_b$, which provides the signal power estimation that does not depend on the receiver gain. In data processing it is necessary to keep in mind that the measured autocorrelation (A_m) is a sum of the detected signal (A) from the radio source under consideration and the surrounding quasi-noise background (A_q) which include as a part the cosmic non-thermal radio background (A_b).

4 Results of the Experiment

4.1 Earth-Spacecraft spatial configuration

On August 18, 1999, the Cassini spacecraft flew by the Earth on its way to Saturn. The SURA transmission was scheduled near midnight (UT=21:30(Aug 18)-00:30(Aug 19)) when the spacecraft was crossing the radar active zone at a distance of 164–191 R_E (Earth Radii) from Earth. In that period the WIND spacecraft was near the perigee of its current orbit and flying from the night side to the morning side of Earth's magnetosphere at a distance of 13.1 to 13.6 R_E. Mutual positions of the Cassini and WIND spacecraft in the sky over the SURA facility site is displayed in an elevation–azimuth plot in Figure 1 (elevation $e = 90° - z$, z: zenith angle).

Figure 1: Sky positions of the Cassini and WIND spacecraft around the SURA beam in Aug 18–19, 1999. The spacecraft trajectories are indicated by solid lines with bold circles and crosses respectively, numbers near the marks denote universal time. The hatched region is the projection of the SURA beam on the sky; dashed lines correspond to first zeros of antenna pattern.

4.2 SURA signal observations

In the session two SURA transmitting sub-modules were emitting independently at 8825 and 9025 kHz with equal power radiating about 240 kW from 21:30 UT, Aug 18 to 00:30 UT, Aug 19. The spacecraft crossed the beam steering plane of the SURA antenna with a $\sim 60°$ South zenith angle. This is more than the regular antenna tilt limits (±40°

from zenith). A special method of phasing of the array feed lines was used to radiate the objects by the subsidiary maximum of antenna pattern. For a zenith angle $z = 60°$ the beam width of the subsidiary maximum at $-3dB$ level is about 36° in the elevation plane and 6° along azimuth direction. Antenna polarizers were configured to radiate circularly polarized waves with ordinary polarization (O-mode). During the session the critical frequency of the F2-layer of the ionosphere dropped gradually from 3.9 to 2.9 MHz. Operating frequencies were well above the ionospheric cut-off in the spacecraft directions.

Signals received by the Cassini HFR and WIND RAD2 at 9025 kHz are displayed in Figure 2 with the abscissa being universal time (UT) in hours and the ordinate being power P in units of $\mathrm{V^2/Hz} \times 10^{14}$. This figure shows the autocorrelation output for the u-monopole of HFR in DF-mode and the Z-antenna output for RAD2 in SEP-mode. The WIND/RAD2 data was also resampled to fit to the Cassini/RPWS/HFR data.

Figure 2: Measured signals onboard the Cassini and WIND spacecraft with log-scale for signal power in units V^2/Hz at 9025 kHz. Dashed lines show cosmic background level for HFR u-monopole and RAD2 Z-antenna. Arrows (marked ON and OFF) denote the times when SURA was switched on and off. A solar type III event near 21:47 UT is also indicated.

Figure 3: Signal-to-background ratios at 9025 kHz for the HFR u-monopole (boldface line) and the RAD2 Z-antenna (lightface line) in the case where the WIND and Cassini spacecraft are normalized to the same distance and to the same receiver's bandwidth (see text). Abscissa is the azimuthal difference $\delta A = A - 9°$ relative to the SURA emission peak.

Figure 3 displays the signal to background ratios $R = (A_m - A_q)/A_q$ versus the azimuth angle: this angle represents the difference between the satellites (i.e. Cassini and WIND) and SURA beam azimuths. The background levels $A_q = 6.4 \times 10^{-14}\,\mathrm{V^2/Hz}$ and $3.4 \times 10^{-17}\,\mathrm{V^2/Hz}$ for RPWS u-monopole and WAVES Z-antenna respectively were used in numerical calculations. It was taking into account that the Cassini was moving away the Earth in limits of $D_C = (164 - 191.2)\,R_E$ while the WIND was round the Earth near perigee with about 13.4 R_E. The signal measured by Cassini /HFR has been scaled to the distance of WIND with factor $((D_C - R_E)/(D_W - R_E))^2$ for every moment. We then see that the shift between the timings of the observed peaks on each spacecraft (see Fig. 2) is thus simply explained by the fact that they are not crossing the beam at the same time.

Observations showed that the SURA signal undergoes strong temporal variations (see Figures 2,3). The main reason for this is the scintillation as well as the Faraday rotation effect in Earth's ionosphere and magnetotail. The typical fluctuation time scale is about 1 min. In order to minimize the influence of these fluctuations in our calibrations, we will average all signals with an integration $T \gg 1\,\mathrm{min}$. A high measurement-to-background data selection was applied to the datasets. As a compromise of both these requirements (minimization of the dispersion due to accidental variations and noise influence) the interval between first zeros of the SURA antenna pattern were chosen for data processing.

In case of the WAVES RAD2 observation we obtain for azimuthal interval $\delta A = [-6°, +6°]$:

$$\langle A_W \rangle = 5.4 \times 10^{-14}\,\mathrm{V^2/Hz} \tag{5}$$

where $\langle\cdots\rangle$ braces denote the averaged values.

For subsequent considerations of Cassini data we will choose the RPWS u-monopole whose colatitude is 96° in the wave frame. We thus suppose that there was almost no flux loss for autocorrelation measurements. Subscript u will be used here for specify any quantity referring to the RPWS/HFR u-monopole. Subtracting the background level $A_{qu} = 6.4 \times 10^{-14}\,\mathrm{V}^2/\mathrm{Hz}$ from the HFR u-antenna autocorrelation measurement A_{mu} , adjusting signal component A_u to the WIND distance with factor $((D_C - R_E)/12.4)^2$, and then averaging the obtained values over the same azimuthal interval ($\delta A = \pm 6°$) we find that the expected SURA signal is $\langle A_u\rangle = 6.6 \times 10^{-11}\,\mathrm{V}^2/\mathrm{Hz}$. We then obtain from Eqs. (3), (4) and (5) the conversion coefficient for the u-monopole that $K_u = 5.0 \times 10^5\, \delta f_C/\delta f_W\, \Omega m^2$. The same calculations for more wide interval $\delta A = [-10°, +10°]$ give $K_u = 4.8 \times 10^5\, \delta f_C/\delta f_W\, \Omega m^2$. Close estimation $4.6\times 10^5\, \delta f_C/\delta f_W\, \Omega m^2$ can be obtained using maxima of smoothed curves of the SURA signal recorded by HFR and RAD2 receivers. The following mean value of the conversion coefficient for the u-monopole at 9025 kHz can then be established:

$$K_u = 4.8 \times 10^5\, \delta f_C/\delta f_W\, \Omega\mathrm{m}^2 \tag{6}$$

The relative accuracy of this result is about ±30% depends mainly on strong intensity fluctuations at both spacecraft location.

At the other operating frequency (8825 kHz) no RAD2 observations were made, as the receiver was in a fixed frequency mode during the experiment.

Autocorrelation outputs for the v and w monopoles are comparatively weaker than the ones for u about 10 dB at both frequencies 8825 and 9025 kHz.

4.3 Solar type III burst observations

We have also studied a solar type III burst that occurred at about 21:47 UT (see Figure 2). In the RAD2 data the event occurred just before the WIND spacecraft flew through a side lobe emission of the SURA beam. A signal increasing up to 14 dB over cosmic background is observed around 21:47:25 UT. Examination of rotating Y-antenna response by the epoch-folding technique shows clearly that direction of arrival in that interval was sunward (Figure 4).

Figure 4: Polar angular diagrams of RAD2 Y-antenna response for solar type III burst (left panel) and for SURA side lobe emission (right panel). Azimuth $A = 0$ corresponds orientation of Y-antenna axis to the sun. Arrows indicate expected emission peaks for sun and ground-based sources in case of short antenna response.

The High Gain Antenna (HGA) of the Cassini spacecraft was pointed toward the sun for thermal reasons. In this position the incident wave from sun is almost normal to the axis of u and v monopoles (colatitudes are 107.9° and 107.6° [Vogl et al., 2004] respectively assuming the source of the type III burst is in the direction of the sun) and they can be used for the conversion coefficient determination.

The event was detected on a single sweep of the HFR because the burst duration (50 sec) was of the order of the receiver sampling time (32 sec). The same procedure used in the case of the SURA signal was applied here. The results for K_u and K_v are shown in Table 1. It was assumed that the flux density of the solar burst is the same at WIND and Cassini positions. Both estimations are consistent with each other within the measurement errors, which are about ±30%. The error bar depends mainly on estimation uncertainty of the SURA emission during the type III burst.

Table 1: Summary of the different estimations of the K coefficient value for the different receivers and antennas.

Observation	K value (Ωm^2)
Galactic Background (WIND/RAD2)	4.1×10^2
SURA+WIND (RPWS/HFR-u)	$(4.8 \pm 1.6) \times 10^5 \times (\delta f_C/\delta f_W)$
Type III (RPWS/HFR-u)	$(3.1 \pm 1.5) \times 10^5$
Type III (RPWS/HFR-v)	$(2.7 \pm 1.4) \times 10^5$
Galactic Background (RPWS/HFR) [Zarka et al., 2004]	$1.7 - 5.1 \times 10^5$

Both estimation of K value based on observations of the SURA signal and a solar type III burst are agree with earch other within the determination accuracy if to take into account that $\delta f_W = 20\,\text{kHz}$, $\delta f_C = 25\,\text{kHz}$ at time of the experiment (see 2.2, 2.3 Sections). Good coincidence of that estimations obtained by two different methods serves as additional validation of the calibration result.

4.4 Discussion

It is interesting to compare the conversion coefficient K obtained here for the SURA signal and type III burst with the one derived by Zarka et al. [2004] through a calibration based on cosmic background measurements during the Cassini-Jupiter flyby. Using Figures 1 and 4b from this paper and relation $A_u = K_u \times S_b$ one can find that the coefficient at 9 MHz is between $\sim 1.7 \times 10^5\,\Omega m^2$ (background level computed on 6 months of data during the Cassini Jupiter flyby) and $\sim 5.1 \times 10^5\,\Omega m^2$ (background measurements in quiet intervals of a few hours far from Jupiter). The values are in agreement with the present estimations (see Table 1) taking into account the calculation accuracy. Now we can not do any recommendation to diminish the obtained uncertainty, future analysis is necessary.

An unexpected result is the low signal level received by v and w monopoles as compared to u during the SURA experiment. As noted above, the angular distance between the Cassini-Earth line and u, v, w antenna axes are respectively 96°, 48° and 141°. The antenna efficiency losses for the v, w monopoles must be about twice those for the u antenna in the short antenna approximation (with a $\sin^2\theta$ variation of the measured power). The actual v, w monopole measurements are about –10 dB lower than the u-monopole ones. It must be underlined that this discrepancy can not be explained by presence of a linear polarization component in the SURA signal because we used averaging of observed intensity over time interval about 30 min which is more long than typical fluctuation time due to Faraday rotation effect in non-stationary Earth ionosphere (about 1 min).

The short antenna approximation is obviously not applicable in the selected frequency range, which is near the main electric resonance (~ 9.5 MHz for the HFR monopoles). The spacecraft body influence has then to be taken into account. The difference between the u and v antenna SURA signals could also be explained by a particularly unfavorable geometrical configuration where the High Gain Antenna is hiding part of the SURA signal for the v antenna.

It was noted above that the SURA emission as well as type III burst emission are subject to wave propagation effects in the magnetotail. For last case that difficulty could be removed using solar events occurring when both spacecrafts are located far from the Earth.

The present type III burst observation is showing that the similar analysis could be used for HFR recurring calibration after the Huygens Probe release. Strong ($S \geq 10^{-18}\,\mathrm{Wm^{-2}Hz^{-1}}$) and prolonged (time duration > 1 min) solar type III bursts would be suitable for such an analysis. The same analysis is also likely to be used to calibrate the STEREO/Waves receivers after they are launched.

5 Conclusion

An absolute calibration of the u-monopole RPWS electric antenna at 9025 kHz using simultaneous observations of the SURA signal by the Cassini and WIND spacecraft is done. The resulting estimate of the conversion coefficient which relates the measured signal in $\mathrm{V^2/Hz}$ to the incoming flux density in $\mathrm{Wm^{-2}Hz^{-1}}$ is consistent with a previous estimation based on cosmic background measurements during the Cassini-Jupiter flyby [Zarka et al., 2004]. A possibility to use the simultaneous observations of solar type III emission aboard Cassini and WIND spacecraft is considered for the type III event during the Aug 18–19, 1999 observation session as an example. It was noted that the WAVES instrument could be used for space calibration of any spacecraft with radio facilities onboard designed for space investigations, in particularly for the future STEREO mission.

Acknowledgements

Yu. T. and A. L. are grateful to INTAS for support (grant N 03-51-5727).

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