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Discrimination between Jovian radio emissions and Saturn electrostatic discharges

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[1] Short vertical streaks in the dynamic spectrum of the Cassini/RPWS (Radio and Plasma Wave Science) receiver in the frequency range of a few MHz can be due to Jovian radio emissions or SEDs (Saturn electrostatic discharges). Although Jupiter is increasingly far from Cassini, the peaks of decametric Jovian arcs can still be detected a few dB above the galactic background, and in some cases they look very similar to the SEDs caused by lightning in Saturn's atmosphere. We show a method for discriminating between these two phenomena by using the ratio of the measured autocorrelations in case the receiver uses at least two antennas. We analyze the special event from July 22, 2003, which was interpreted as the first indication of SEDs at a time when the spacecraft was still at a distance of 1.08 AU from Saturn, and find that it originated from Jupiter.

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1. Introduction

[2] In 2004 Cassini detected the radio signatures of about 5400 SEDs, which are believed to stem from lightning discharges in Saturn's atmosphere [*Fischer et al.*, 2006a]. The impulsive bursts were recorded from a frequency of about 1 MHz up to the upper limit of the HFR (High Frequency Receiver) of the RPWS instrument [*Gurnett et al.*, 2004] at 16 MHz. In the same frequency range one can find the so-called Jovian decametric arcs, which are magnetospheric radio emissions from Jupiter that appear arc-like (somewhat like parentheses) in the time-frequency spectrogram. Due to the large distance of Jupiter, Jovian arcs do not appear as smooth emissions, but they are quite bursty and, in this way, they can mimic the SEDs. In some cases the Jovian arcs show a clear vertex, making it easy to identify them visually. In the frequency band of interest the HFR acts as a sweeping receiver, and the broadband SEDs appear as narrow-banded vertical streaks in the time-frequency spectrogram due to the fact that they are detected only in the few channels being sampled during the short duration of the burst. As lightning discharges pop up randomly in time, the SEDs generally appear equally distributed in frequency above the ionospheric cutoff frequency. It is quite easy to identify intense SED episodes lasting for several hours, but sometimes there can be also short episodes lasting several tens of minutes with a few tens of bursts, and the latter can look like Jovian emissions. An additional hint is the phase of Io as seen from the observer Cassini: if the Io-phase is close to 90° or 270° a Jovian emission is more likely.

[3] Figure 1 shows a spectrogram of some impulsive bursts detected by the Cassini RPWS instrument on July 22 (DOY 203), 2003, as compared to the SED episode A1 from July 13 (DOY 195), 2004. Episode A1 was the first SED episode of storm A recorded by Cassini RPWS after Saturn Orbit Insertion [*Gurnett et al.*, 2005; *Fischer et al.*, 2006a]. The bursts from 2003 were interpreted by *Gurnett et al.* [2005] as the first indication of lightning from Saturn. At that time the spacecraft was on its way from Jupiter to Saturn at a distance of about 1.08 AU from Saturn. During this event the HFR was in the so-called polarimeter mode, where the autocorrelations and cross-correlations of and between two different RPWS antennas were measured. For electric field measurements the RPWS has three electric monopole antennas E_u, E_v, E_w of 10 m in length, and the monopoles E_u and E_v can be combined to form the dipole E_x [*Gurnett et al.*, 2004]. During the event of DOY 203, 2003, the HFR performed sweeps every 32 seconds from 2075 to 16075 kHz in 200 kHz steps with an integration time of 80 ms. The spectrum on the left side of Figure 1 shows the autocorrelation measurement of the dipole E_x, and one can see several bursts around 20:30 SCET in the frequency range from about 4 to 10 MHz. The limited frequency range of the event (compared to the SED episode A1) is a first argument against the SED source assumption, although not a conclusive one. A second "concern" is the extremely large source power this SED event would have due to the enormous distance to Saturn: SEDs were measured by Voyager 1 only during some days around closest approach to Saturn, and they had a source power around 100 W Hz^{-1} [*Zarka and Pedersen*, 1983]. Similarly, for all SEDs recorded by Cassini RPWS in 2004 at Saturn, a source power of 50 to 100 W Hz^{-1} was found [*Fischer et al.*, 2006b; *Zarka et al.*, 2006]. In section 4 we will show that the "2003–203 event" would have a source power about 1000 times greater than all other SEDs detected so far. If we take the July 2003 event for a real SED event, our general idea of the power of lightning flashes from Saturn would be significantly altered (by three orders of magnitude!). Compared to a typical terrestrial flash, the source power of a

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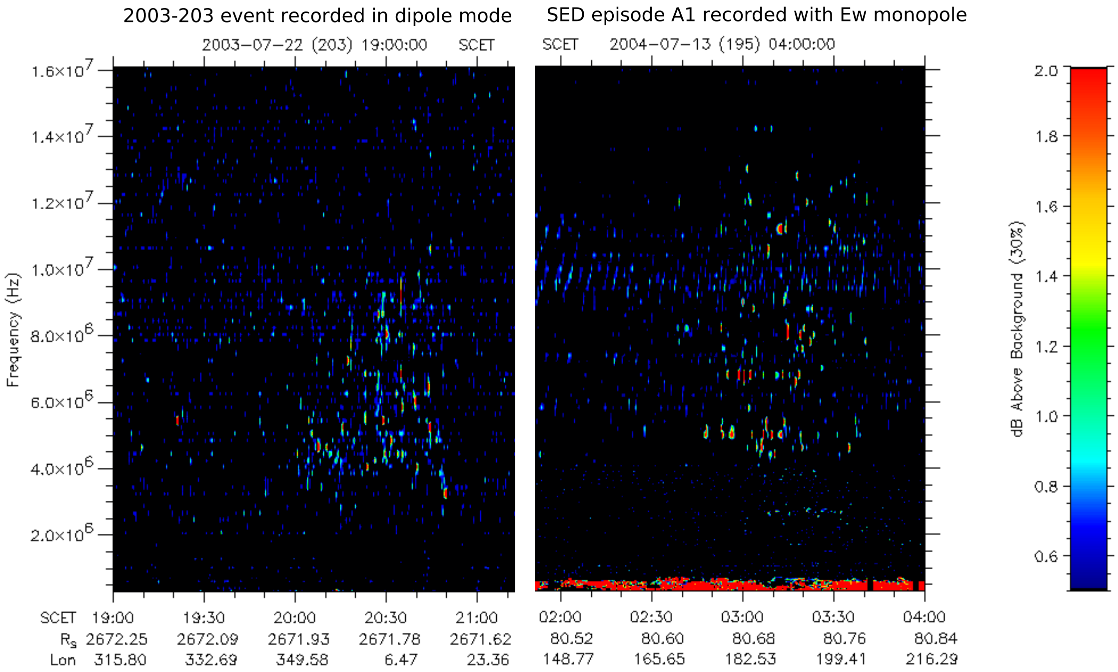

Figure 1. Dynamic spectra of the (left) event on DOY 203, 2003, as measured by the dipole E_x, and (right) SED episode A1 from DOY 195, 2004, as measured by the monopole E_w. The frequency scale on the left and the color bar showing the intensity (with 30% background division) on the right are valid for both spectra. Note the different distances when the events were recorded (around 2672 R_S (Saturn radii) compared to 81 R_S). The red emission on the right side below 1 MHz is Saturn Kilometric Radiation.

typical Voyager recorded SED is about 1000 to 10,000 times greater (comparable to a terrestrial "superbolt"), hence, the 2003–203 event would have a source power at least a million times greater than a typical lightning flash on Earth. The source powers (in the frequency range of a few MHz) were all calculated assuming isotropic radiation. For a tortuous lightning channel this assumption is not so far from reality, at least a broad beamwidth similar to a dipole can be expected. On the other hand, Jovian decametric emissions are known to be narrowly beamed emissions with a far reach, and their detection from a distance of several AU even with the antennas on-board Cassini is not unusual. During the July 2003 event Cassini was at a distance of 6.2 AU from Jupiter, and the flux density of this event is only a few dB above background, hence it should be around 10^{-19} W m^{-2} Hz^{-1} (see also section 4) according to the galactic background model of *Dulk et al.* [2001]. Assuming Jupiter to be the source, and normalized to a distance of 1 AU from Jupiter, the flux density would be $4 \cdot 10^{-18}$ W m^{-2} Hz^{-1}, which is consistent with the peak intensities of the Jovian radio spectrum as shown by *Zarka et al.* [2004]. Other concerns about the 2003–203 event being caused by SEDs are: (1) there seems to be intensity in-between the bursts, and the emission seems to cover an area in the time-frequency plane (see Figure 1), (2) it could be an Io related Jupiter emission as the Io-phase is 98°, (3) there are a lot of Jovian arcs in the days around DOY 203 (observed by RPWS), and many of them are 42 hours apart (Io's orbital period), and (4) the number of bursts per frequency and time interval is higher than for typical SED episodes with a similar number of bursts. So, the question we try to answer in this paper is clear: Is the event from DOY 203, 2003, an SED episode or a Jovian emission?

2. Mathematical Formalism

[4] The formalism is based on the well-known relation between the voltage V at an antenna terminal induced by the incident wave electric field $\vec{E}$, and the so-called effective length vector $\vec{h}$ of the antenna:

$$V = \vec{E} \cdot \vec{h} \tag{1}$$

The effective length vectors $\vec{h}$ of the RPWS antennas were determined using different methods [*Rucker et al.*, 1996; *Vogl et al.*, 2004; *Cecconi and Zarka*, 2005], one of them being the numerical method of wire-grid modeling [*Fischer et al.*, 2001]. The RPWS HFR can measure the autocorrelation $\langle VV^* \rangle$, which is given by the following equation:

$$\begin{aligned}\langle VV^* \rangle &= \langle \vec{E} \cdot \vec{h} (\vec{E} \cdot \vec{h})^* \rangle = \langle |\vec{E} \cdot \vec{h}|^2 \rangle = \langle |\vec{E} \cdot \vec{h}_p|^2 \rangle \\ &= \langle |\vec{E}|^2 |\vec{h}_p|^2 |\cos(\alpha)|^2 \rangle = \frac{1}{2} |\vec{h}_p|^2 \langle |\vec{E}|^2 \rangle,\end{aligned} \tag{2}$$

with the asterisk * denoting the complex conjugate, and $\langle \rangle$ a time-averaging operation. The calculation in the equation above is performed in the so-called wave frame, where $\vec{E} \cdot \vec{k} = 0$ with $\vec{k}$ as the wave vector perpendicular to the wave plane. Hence, the effective length vector $\vec{h}$ can be replaced by $\vec{h}_p$, which denotes the projection of $\vec{h}$ onto the wave plane. Finally, α is the angle between $\vec{E}$ and $\vec{h}_p$. Under the assumption of unpolarized or circularly polarized waves,

α has all possible values with the same probability, hence, the time average $\langle|\cos^2(\alpha)|\rangle = \frac{1}{2}$. (Even for elliptically polarized waves with a small degree of linear polarization Equation (2) is a good approximation.) Equation (2) holds for an arbitrary antenna, and we can set it up for the dipole E_x as well as for the monopole E_w:

$$\langle V_x V_x^* \rangle = \langle S_{Flux} \rangle Z_0 |\vec{h}_{p,x}|^2 \quad \text{and} \quad \langle V_w V_w^* \rangle = \langle S_{Flux} \rangle Z_0 |\vec{h}_{p,w}|^2 \qquad (3)$$

Additionally we used the identity $\langle|\vec{E}|^2\rangle = 2\ Z_0 \langle S_{Flux}\rangle$ with $Z_0 = 120\pi\Omega$ as the impedance of free space, and $\langle S_{Flux}\rangle$ as the incident power flux in W m^{-2} Hz^{-1}. $\langle V_x V_x^*\rangle$ and $\langle V_w V_w^*\rangle$ are the measured autocorrelations (in V^2 Hz^{-1}) of the dipole E_x and monopole E_w, respectively. $\vec{h}_{p,x}$ and $\vec{h}_{p,w}$ are the projections of the effective length vector of the x-dipole and the w-monopole onto the wave plane (in m). These two measurements of the incident wave with the flux $\langle S_{Flux}\rangle$ are performed simultaneously. A simple division of the two equations above shows that the ratio of the measured autocorrelations is equal to the ratio of the two squared magnitudes of the projections of the respective effective length vector onto the wave plane:

$$\frac{\langle V_w V_w^* \rangle}{\langle V_x V_x^* \rangle} = \frac{|\vec{h}_{p,w}|^2}{|\vec{h}_{p,x}|^2} \qquad (4)$$

We have arrived at our basic equation which will be applied for the discrimination of Jovian emissions from SEDs for the 2003–203 event. From Cassini attitude data we know the position of Jupiter or Saturn with regard to the fixed spacecraft coordinate system (for the definition of this system see *Gurnett et al.* [2004] or *Vogl et al.* [2004]), and the effective length vectors for all RPWS antennas are well known in this coordinate system in the quasistatic frequency range (frequencies where short dipole approximation is valid). Under the assumption that our radio bursts either stem from Saturn or from Jupiter, we can calculate the two ratios $|\vec{h}_{p,w}|^2/|\vec{h}_{p,x}|^2$ for waves from Jupiter and Saturn, respectively. If these two ratios are not too close to each other (depends on the exact geometrical situation) a decision about the direction of incidence is possible simply by looking at the ratio $\langle V_w V_w^*\rangle/\langle V_x V_x^*\rangle$ of the measured signals. We note that for $\langle V_w V_w^*\rangle$ and $\langle V_x V_x^*\rangle$ we have of course to take the measured antenna signal minus the galactic background radiation. The background was calculated hourly at each frequency channel as the mean intensity after the elimination of strong signals lying four standard deviations above the mean intensity. This relatively simple technique is, in fact, just the basic principle of the highly sophisticated "direction-finding" (DF) technique, where the polarization and the direction of an incoming wave (in the quasistatic frequency range) can be fully determined by using the autocorrelation and cross-correlation measurements of three non-coplanar antennas. Hence, as the bursts of the 2003–203 event were above the quasistatic frequency range, and only two antennas were used, a full DF analysis cannot be done in this case. We only want to make a discrimination between two supposed incoming wave directions, so it is sufficient to look at the ratio of the measured autocorrelations of only two antennas, and we could call this technique "direction discrimination". The only difficulty comes from the fact that the quasistatic frequency range of the RPWS goes just up to about 1.5 MHz. Therefore, the so-called wire-grid modeling technique is used to evaluate the effective length vectors also for the frequencies above the quasistatic range.

[5] Wire-grid modeling is a numerical simulation method where an antenna system is represented by a suitable wire-grid model. As a spacecraft normally has conducting surfaces, a wire-grid of the whole spacecraft including the antennas has to be constructed. The currents on the wires are calculated by means of an electromagnetic code, which numerically solves the underlying boundary value problem for the current density $\vec{J}_F$ over the surface F of the whole antenna system (including spacecraft body). With these currents the effective length vector $\vec{h}$ can be calculated by the following integration [*Sinclair*, 1950; *Collin and Zucker*, 1969]:

$$\vec{h} = \frac{1}{I} \oint \vec{J}_F(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} dF \approx \frac{1}{I} \sum_{wires} \int I_n(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} \vec{dl}, \qquad (5)$$

where I denotes the current through the antenna feed, $\vec{k}$ the wave vector of the incident wave, and $\vec{r}$ the coordinates of antenna elements. The second integral applies if a wire-grid modeling of the antenna system is performed. In this case the sum runs over all wire segments with the path integrals to be taken along the wire center axes, $I_n(\vec{r})$ being the current through the n-th wire and $\vec{dl}$ the infinitesimal line element. For wavelengths exceeding the dimensions of the spacecraft ($\vec{k} \cdot \vec{r} \ll 1$, quasistatic frequency range) the imaginary part of the effective antenna length vector can be neglected (by setting $e^{-i\vec{k}\cdot\vec{r}} = 1$). Above the quasistatic range $\vec{h}_{p,x}$ and $\vec{h}_{p,w}$ are, in general, *complex vectors depending on the frequency and the direction of wave incidence*. Nevertheless, since the frequency of the emission is known, the expected ratio $|\vec{h}_{p,w}|^2/|\vec{h}_{p,x}|^2$ can be calculated for the two different directions of Jupiter and Saturn.

3. Demonstration of "Direction Discrimination" Using an SED-Episode

[6] Before applying this technique to the event in 2003, we first illustrate it with the prominent SED episode A1 (see right spectrum of Figure 1) recorded by RPWS on July 13 (DOY 195), 2004, of the storm A [*Gurnett et al.*, 2005]. At that time the instrument was in the direction-finding (DF) mode, and we take the measured autocorrelations of the v-antenna (no dipole measurement here) and the w-antenna, hence $\langle V_w V_w^*\rangle/\langle V_v V_v^*\rangle = |\vec{h}_{p,w}|^2/|\vec{h}_{p,v}|^2$ is our basic equation. In Figure 2 one can see the theoretically expected ratios as a function of frequency calculated by our model for an incident wave direction of Saturn (solid line) and Jupiter (dashed line). We only show the first 1.5 hours of this SED episode as the spacecraft had a slightly different attitude later. Saturn remained in practically the same direction of $\theta_{Sat} = 90°$and $\phi_{Sat} = 270°$ (the slight change of ϕ_{Sat} from 267° to 272° is negligible), and Jupiter is located at $\theta_{Jup} = 108°$ and $\phi_{Jup} = 148°$ in the fixed spacecraft frame of Cassini (θ and ϕ are the colatitude and azimuth, respectively). It is very clear from Figure 2 that the bursts should originate from Saturn, and the wire-grid modeling seems to work pretty well also at higher frequencies. We have also drawn error

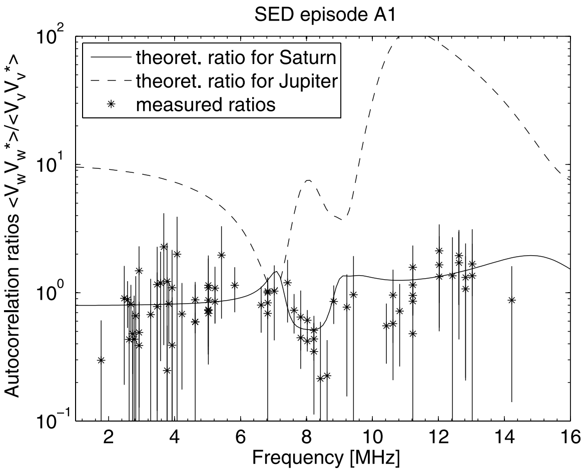

Figure 2. Modeled ratios of the autocorrelations assuming waves from Saturn (solid line) and Jupiter (dashed line) as a function of frequency during episode A1 of the SED storm A (first 1.5 hours, DOY 195, 02:30–04:00 SCET, 2004). The measured ratios are plotted as asterisks with error bars.

bars corresponding to an absolute error of 0.5 dB for each autocorrelation (error of antenna signal plus error of background), and for the relative error of the autocorrelation ratio we just added the relative errors of numerator and denominator. Autocorrelation measurements with the RPWS HFR have a digital quantization interval of 1 bit corresponding to 0.375 dB [*Gurnett et al.*, 2004]. The so-called A/D error equals half the quantization interval, which is ~0.2 dB. As the background was subtracted from our antenna signal, an error similar to the background fluctuation (~0.3 dB representing the one sigma level) has to be included. Hence, the absolute error of the burst signal equals 0.2 + 0.3 = 0.5 dB.

[7] About 1000 SEDs were recorded by Cassini RPWS in the DF-mode during the storms A and B in July and August 2004, respectively [*Fischer et al.*, 2006a]. We also looked at all other episodes from the two storms A and B by creating similar plots as in Figure 2: From 15 episodes of storm A at least 9 showed a very clear tendency towards an emission from Saturn, and for 6 there was either a non-favorable geometry (modeled ratios too close), not enough SEDs, or SEDs of too low intensity to make a clear discrimination between Jupiter and Saturn. Similarly, for the 16 episodes from SED storm B at least 8 showed clearly that the emission comes from Saturn. Not a single episode from the SED storms A and B recorded in 2004 showed measured autocorrelations with a tendency towards waves coming from Jupiter, which should emphasize the principal capability of the "direction discrimination" technique.

4. The 2003–203 Event

[8] During the event of DOY 203, 2003, around 20:30 SCET the spacecraft did not perform any maneuver. Hence, the directions of Saturn and Jupiter were constant within a few tenth of a degree with Saturn at $\theta_{Sat} = 65°$ and $\phi_{Sat} = 174°$, and Jupiter at $\theta_{Jup} = 139°$ and $\phi_{Jup} = 352°$ in the fixed Cassini spacecraft frame. The angle between the two gas giants as seen from Cassini was 157°. The angles between Jupiter and the quasistatic effective length vectors of the w-monopole and the dipole were 45° and 49°, respectively. As these angles are quite similar and the effective length of the monopole is about half the effective length of the dipole, the predicted autocorrelation ratio for radio emissions from Jupiter should be around 1:4 as the projections of the effective length vectors have to be squared according to Equation (4). The ratio for emissions from Saturn turns out to be around 1, as the angles between Saturn and the effective length vectors of monopole and dipole were 65° and 26°, respectively. Figure 3 shows that these ratios do not change so much with frequency up to about 6 MHz, and the behavior is more complicated at the antenna resonance frequencies around 8 MHz. The asterisks in Figure 3 denote the measured ratios of the burst and the numbers give the intensity of the respective burst in dB above the background as measured by the dipole. There is a clear tendency for the emissions to come from Jupiter as can be seen in Figure 3, and there is not even a single burst which is close to the modeled ratio for waves coming from Saturn! The bursts with a higher intensity (e.g. greater than 3 dB) are clearly very close to the modeled ratio for Jupiter, and the error bars were done in the same way as already explained in section 3 for Figure 2. The autocorrelation measurements of low intensity bursts have a higher relative error compared to bursts of high intensity. This explains the clustering of bursts with higher intensity close to the modeled curve, whereas low intensity burst show in general a larger deviation. (Another reason for a deviation from the curve could be a burst with a significant component of linear polarization.) The bursts were identified using a computer algorithm where the autocorrelation values of the dipole of successive sweeps were compared at fixed frequency channels, and the burst has to be a certain threshold value (1.2 dB) above the background.

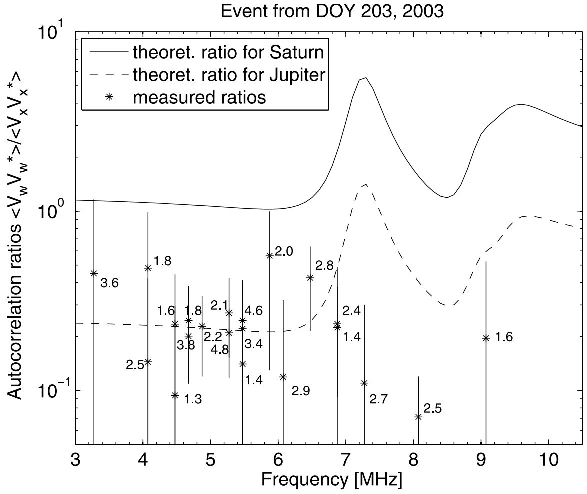

Figure 3. Modeled ratios of the autocorrelations assuming waves from Saturn (solid line) and Jupiter (dashed line) as a function of frequency during the event on DOY 203, 2003, around 20:30 SCET. The ratios of the autocorrelations measured by the w-antenna and the dipole are plotted as asterisks with error bars. The numbers denote the intensity of the respective single burst in dB above the background as measured by the dipole.

[9] Additionally we tested several successive events before and after the most prominent event, on DOY 203, 2003, in the same way. Either they showed a tendency for a Jovian emission, sometimes the geometrical situation was unfavorable, or the instrument was in a mode using just one antenna. Particularly the bursts at DOY 204 (around 16:00 SCET) and DOY 206 (around 09:30 SCET) showed a clear tendency to stem from Jupiter and not from Saturn. The latter two events together with the prominent 2003–203 event did mimic a 10 hour 10 minute periodicity similar to the SED recurrence period found by Voyager 1, which was the main reason why these 2003 events were first thought to be SEDs. We also tested events where the arc-like structure in the dynamic spectrum indicated a Jovian arc (DOY 221, 2003, around 13:30 SCET is a nice example), and in fact, we got a clear tendency for a Jovian emission from the measured autocorrelation ratios.

[10] A second closely related argument comes from the calculation of the average power flux of all bursts of an episode: The two equations (3) show that the flux $\langle S_{Flux} \rangle$ of the incoming wave can be calculated for each antenna separately just by dividing the respective autocorrelation by the squared magnitude of the projection of the respective effective length vector (and the impedance of free space). As we measure the emission with both antennas at the same time we should arrive at similar values for both independent measurement. Assuming the source from the direction of Jupiter for the 2003–203 event, we arrive at an average flux of $0.97 \cdot 10^{-19}$ W m^{-2} Hz^{-1} for the measurement with the dipole, and at $0.87 \cdot 10^{-19}$ W m^{-2} Hz^{-1} for the average flux measured by the w-monopole. These two values are in agreement within $\sim$10%. On the other hand, assuming Saturn to be the source of the emissions, the respective average fluxes are $3.7 \cdot 10^{-19}$ W m^{-2} Hz^{-1} for the dipole measurement, and $0.7 \cdot 10^{-19}$ W m^{-2} Hz^{-1} for the w-monopole measurement. There is a factor greater than 5 between the two measurements, and our conclusion from this is clear: the assumption that these emissions stem from Saturn cannot be true! From the flux measurements one can calculate the so-called source power P by assuming radiation from an isotropic source with $\langle P \rangle = 4\pi r^2 \langle S_{Flux} \rangle$ with r as the distance between Cassini and the source of radiation. As already mentioned in the introduction, if the 2003 emissions were SEDs, these source powers would be unrealistically high with values of 120 kW Hz^{-1} (dipole measurement) or 23 kW Hz^{-1} (monopole measurement). We evaluated the average source powers of all SEDs from the SED storm A in 2004: Using the autocorrelations from the v-antenna we arrived at 72 W Hz^{-1}, and using the autocorrelations from the w-antenna we got 60 W Hz^{-1}, which are in good agreement with each other.

5. Conclusion

[11] We have presented the mathematical formalism of a method that could be called "direction-discrimination", which can be used to discriminate between possible radio sources in case the emission is measured by at least two antennas. While this is rather elementary in the quasistatic frequency range, we extended this technique also to higher frequencies with the method of wire-grid modeling, where complex effective length vectors of antennas can be calculated as a function of frequency and direction of incidence. We have applied "direction-discrimination" to SED episodes, and to the special event of DOY 203, 2003, where emissions in the MHz range were first assumed to be SEDs. By using the ratio of the autocorrelation measurements we have shown that the emissions from and around DOY 203, 2003, are not due to SEDs, but in fact are Jovian radio emissions.

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