FIRST RESULTS ON THE CALIBRATION OF THE CASSINI RPWS ANTENNA SYSTEM

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Abstract

The calibration of the Cassini RPWS antenna system is an important issue on its mission to Saturn and Titan. Using radio waves emitted from Jupiter and several roll maneuvers done by the Cassini spacecraft in November 2000, we analyze voltage measurements at different frequencies to obtain relevant quantities like the Stokes parameters of the waves, effective length, co–latitude and azimuth angles of each (monopole) antenna. Our investigations are based on single value decomposition technique which provides a "best estimation" of each parameter. We found that former results based on the concept of "rheometry" are in good agreement with recent spacecraft data.

1 Introduction

The Cassini/Huygens mission is designed to visiting Saturn and Titan and one goal of this mission is the investigation of Saturnian radio emissions using the Radio and Plasma Wave Science (RPWS) experiment [Gurnett et al., 2001b]. The RPWS antenna system consists of three conducting monopoles which are short compared with the wavelength of the incoming waves. It has to be noted that exact knowledge of the antenna's effective length vectors is necessary to obtain accurate observations. A first attempt on determining these vectors was done by Rucker et al. [1996] based on the concept of rheometry, where a realistic spacecraft model (scale 1:30) was immersed in a water–filled tank and the response of the electric field, generated by two parallel plates of a capacitor, on the model antennas have been analyzed.

In November 2000, the Cassini/Huygens spacecraft was at distances to Jupiter of approximately 600 R_J (November 15, 2000) to 350 R_J (November 30, 2000), where R_J denotes

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the radius of Jupiter. The closest approach to Jupiter occurred on December 30, 2000. In this time roll maneuvers around its x and y–axes were done to determine the co–latitude and azimuth of the u/v antennas (as defined in Gurnett at al., [2001b]). These maneuvers provide the possibility to determine the maxima and minima of the antenna patterns with respect to the electric field, i.e., the antenna position at minimum response occurs when the antenna is most nearly parallel to the direction to the source, when the wave electric field is nearly perpendicular to the antenna.

In the present paper we analyze voltage measurements during these roll maneuvers; further on Jupiter's angular position in the spacecraft reference frame is needed. We focus on these two aspects in the next section. For reference we summarize in Table 1 the roll maneuvers mentioned above, where DOY is the day of year, SCET refers to the spacecraft event time and CDA denotes the Cosmic Dust Analyzer articulation position onboard the spacecraft. We note that CDA is very close to the root of the RPWS antennas and can be articulated. Thus, different CDA orientations have to be taken into account to study the influence of the CDA on the effective length vectors of the RPWS antennas. The spacecraft

DOY	SCET	Rotation	CDA
320 16:12–01:04	15:41–00:33	x–axis rotation for u antenna	2 deg
325 15:52–00:44	15:21–00:13	x–axis rotation for u antenna	270 deg
330 15:32–00:24	15:01–23:53	x–axis rotation for u antenna	135 deg
335 15:13–00:05	14:41–23:33	x–axis rotation for u antenna	2 deg
340 14:53–23:45	14:21–23:13	y–axis rotation for u antenna	2 deg

Table 1: Cassini Jupiter pre–encounter roll maneuvers done in November, 2000.

was rotated about its x–axis such that during one phase of each rotation the u antenna would be nearly parallel to the direction to Jupiter. At another phase, the v antenna would be nearly parallel to the direction to Jupiter. Sweeping the antennas through this orientation provides optimum approach to calibrate the u/v antenna. Spacecraft thermal considerations did not allow the w antenna calibration maneuvers prior to closest approach. Therefore, the w antenna is addressed after Jupiter closets approach when the changing geometry allows rotations which should provide good resolution for that antenna.

2 Basic concept

Our analysis is based on the direction finding technique developed by Ladreiter et al. [1995]. As input parameters we use squared voltage measurements, $< V_n V_k^* >$, where $< \ >$ is the time averaging operation, * is the complex conjugate, and V_n, V_k denote the voltages received on antennas n and k, respectively. In short, we search for a solution where the weighted squares sum of the differences between the RPWS observations, y_i^{obs}, and the model predicted values, y_i^{mod}, becomes a minimum,

$$\chi^2 = \sum_{i=1}^{N} W_i \Big[y_i^{obs} - y_i^{mod}(\mathbf{X}_j) \Big]^2 = Min. \tag{1}$$

Here, the y_i^{obs} represent the data to be measured by the RPWS experiment, i.e., $< V_1 V_1^* >$, $< V_2 V_2^* >$, $< V_3 V_3^* >$, $\Re < V_1 V_3^* >$, $\Re < V_2 V_3^* >$, $\Im < V_1 V_3^* >$, and $\Im < V_2 V_3^* >$, the y_i^{mod} denote our modeled quantities [see Ladreiter et al., 1995], and quantity W_i refers to the weights reflecting the uncertainty of each y_i^{obs}. Vector $\mathbf{X}_j$ contains the unknown parameters, i.e., the Stokes parameters and the direction of incidence of the received electromagnetic wave or the relevant antenna parameters, i.e., effective length, co–latitude, and azimuth of the antennas. Our analysis is based on parameter resolution and singular value decomposition technique, which is well described in Ladreiter et al. [1995] and references therein.

Further needed is the angular position of Jupiter, as seen from a Cassini centered coordinate system. Therefore we use the orbit position of Cassini in the so–called Jupiter–Solar–Ecliptic coordinate system, JSE, where X points to the Sun, Z is normal to Jupiter's orbital plane, and Y completes the right–handed triad). The corresponding ephemeris and attitude data are provided by the RPWS team home page[1].

As an example we compute the angular position (co–latitude and azimuth) of Jupiter as seem from Cassini on November 15, 15:00 SCET, 2000. Cassini's orbit position vector (ephemeris data) is

SCET	X (Rj)	Y (Rj)	Z (Rj)	R (Rj)
2000 320 15 00 00.000	574.868	-179.677	6.327	602.327

We note that one has to change the sign of the position vector to specify Jupiter's position as seen from Cassini. The corresponding attitude data are (normalized)

SCET	S/C X (JSE)	S/C Y (JSE)	S/C Z (JSE)
2000-320T15:00:00.000	-0.992757	-0.014106	-0.119308
	-0.119173	-0.010056	0.992823
	-0.015204	0.999850	0.008302

[1] `http://www-pw.physics.uiowa.edu/~tfa/cassatt.html`

This 3×3 matrix can be used as a transformation matrix. Using the transpose of it and performing a simple matrix multiplication leads to

$$\begin{pmatrix} -0.992757 & -0.119173 & -0.015204 \\ -0.014106 & -0.010056 & +0.999850 \\ -0.119308 & +0.992823 & +0.008302 \end{pmatrix} \times \begin{pmatrix} -574.868 \\ +179.677 \\ -6.327 \end{pmatrix} = \begin{pmatrix} 549.388 \\ -0.024 \\ 246.921 \end{pmatrix}. \quad (2)$$

Hence, the standard polar coordinate angular position is (T. Averkamp, priv. comm.)

$$\theta = \arccos\left(\frac{246.921}{602.327}\right) = 65.8^\circ \quad \text{and} \quad \phi = \arctan\left(\frac{-0.024}{549.388}\right) = -0.0025^\circ.$$

3 Results

As an illustrative example we analyse spacecraft observations done on November 15, 2000 (DOY 320) as shown in Figure 1. From top to bottom we plot the frequencies of the observed electromagnetic wave intensities and the corresponding squared voltages, $< V_1V_1^* >$, $< V_2V_2^* >$, $< V_3V_3^* >$, $\Re < V_1V_3^* >$, $\Re < V_2V_3^* >$, $\Im < V_1V_3^* >$, and $\Im < V_2V_3^* >$ as a function of spacecraft event time (SCET). Note that quantities $\Re < V_1V_3^* >$, $\Re < V_2V_3^* >$, $\Im < V_1V_3^* >$, and $\Im < V_2V_3^* >$ are normalized quantities. In addition, we perform our analysis for all frequencies measured by he RPWS antenna system (top panel of Figure 1). As further can be seen from the figure only the time interval from 19:00 till 23:00 SCET is of interest.

As mentioned in Section 2 we compute Jupiter's position as seen from Cassini via the ephemeris and attitude data. Because of the distance to Jupiter we assume that the angular distance between the Jovian radio source and the center of Jupiter is negligible. In Figure 2 we show the computed angles, θ (co–latitude) and ϕ (azimuth) as a function of spacecraft event time in the interval 19:00 till 23:00 SCET. We note that the data gaps in both time series correspond to the time resolution of the spacecraft observations (Figure 1).

In our analysis, we first compute the Stokes parameters. As input parameters we use the results obtained from rheometry experiments [Rucker et al., 1996] (with or without the Huygens probe (HP)), which are shown in Table 2.

Antenna	HP On: θ	ϕ	HP Off: θ	ϕ
u	107.9	16.5	107.6	16.3
v	107.3	162.7	106.4	163.5
w	31.4	91.2	30.8	92.9

Table 2: Effective height directions of the RPWS antenna system obtained from rheometry.

We found that in the time interval 19:00 till 23:00 SCET the averaged values of the Stokes parameters are $Q = 0.0$, $U = -0.3$, and $V = 0.9$ (note that $S=\sqrt{Q^2+U^2+V^2}$).

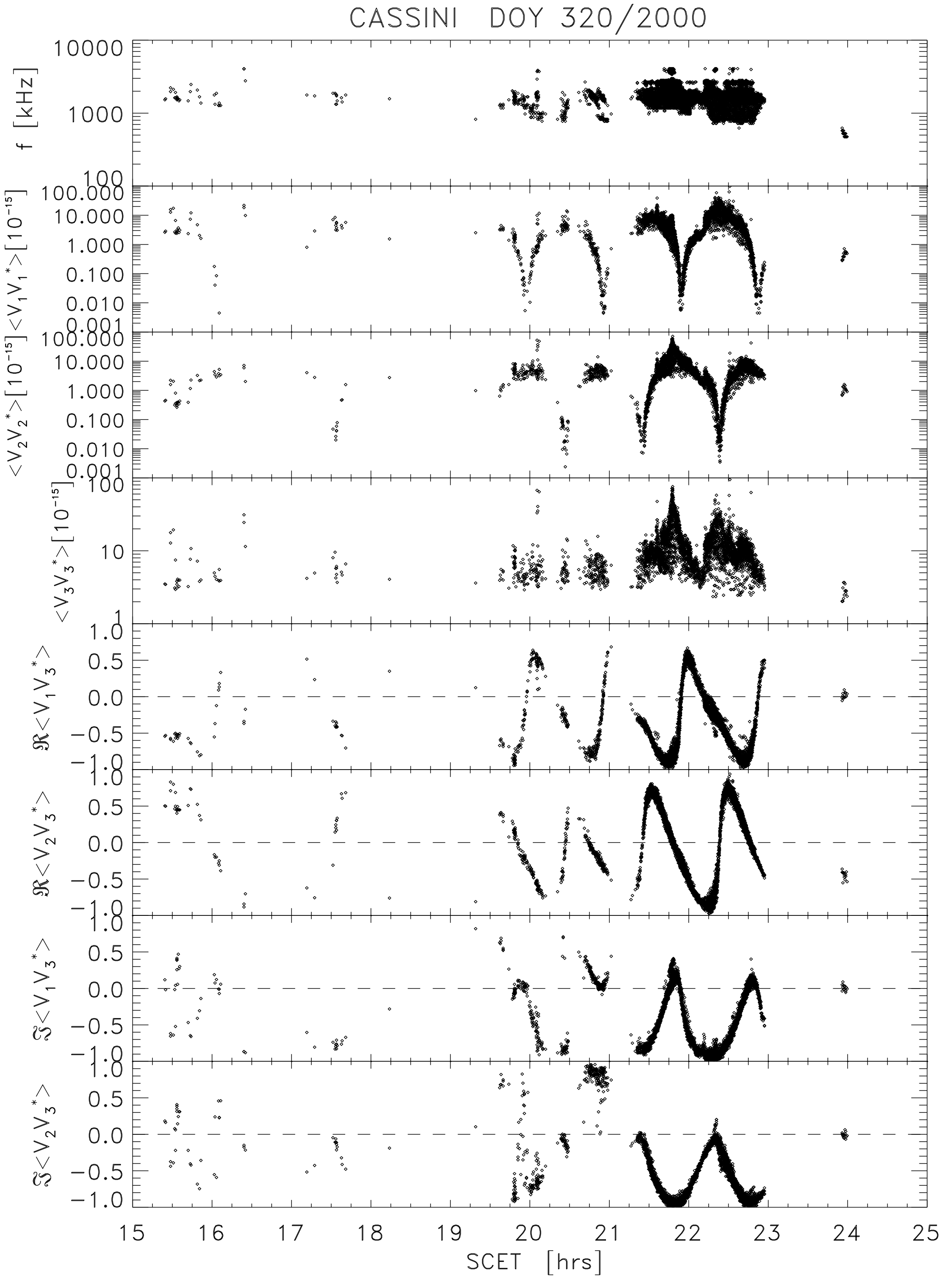

Figure 1: Cassini spacecraft observations on November 15, 2000. From top to bottom we show the observed frequencies and the corresponding squared voltages as a function of spacecraft event time (SCET). We note that $\Re < V_1V_3^* >$, $\Re < V_2V_3^* >$, $\Im < V_1V_3^* >$, and $\Im < V_2V_3^* >$ are normalized quantities.

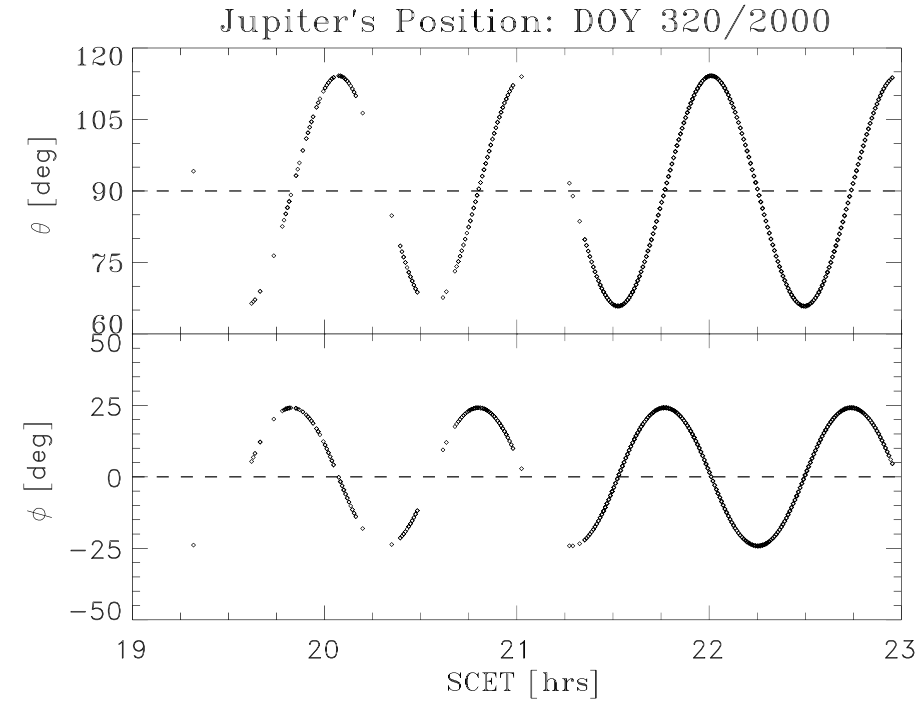

Figure 2: Jupiter's position as seen from Cassini on DOY 320, 2000.

In a further step we use the averaged values of the Stokes parameters and search for a best estimation regarding the co–latitude and azimuth of each antenna. As mentioned above we work with parameter resolution, which is described by the so–called resolution matrix, R, [see Connerney, 1981, and references therein] relating the solution $\mathbf{X}(l)$ using l eigenvectors which represents the traditional least squares solution (equation (1)), after Ladreiter et al. [1995],

$$\mathbf{X}(l) \;=\; R(l)\,\mathbf{X}. \tag{3}$$

Our approach asks for high parameter resolution, i.e., our "best estimation" comes close to the "best fit".

Figure 3 shows a) the resolution of the direction of the u antenna, b) the resolution of the v antenna and c) the resolution of the w antenna using voltage measurements of DOY 320. It has to be noted that the roll maneuver on DOY 320, 2000 was designed for calibrating the u and v antennas. Thus, we expect good parameter resolution for these two RPWS elements. Indeed, panels a) and b) show time intervals, where the parameter resolution for both angles goes up to unity, e.g., at approximately 20:00 SCET, or 21:00 SCET. As a consequence of the roll maneuver, the resolution of the two angles for the w antenna, specifically for the azimuth ϕ_3, is low (see Figure 3c)). Thus, post–Jupiter roll maneuvers will be used to perform the calibration of the w antenna.

As a last step in our analysis we search for directions of the u/v antennas, where the parameter resolution of the co–latitude and azimuth is high, i.e., 99.9 %. Figure 4 shows a) the results for the direction of the u antenna and b) results for the co–latitude and azimuth of the v antenna of DOY 320/2000 for high parameter resolution, i.e., 99.9%,

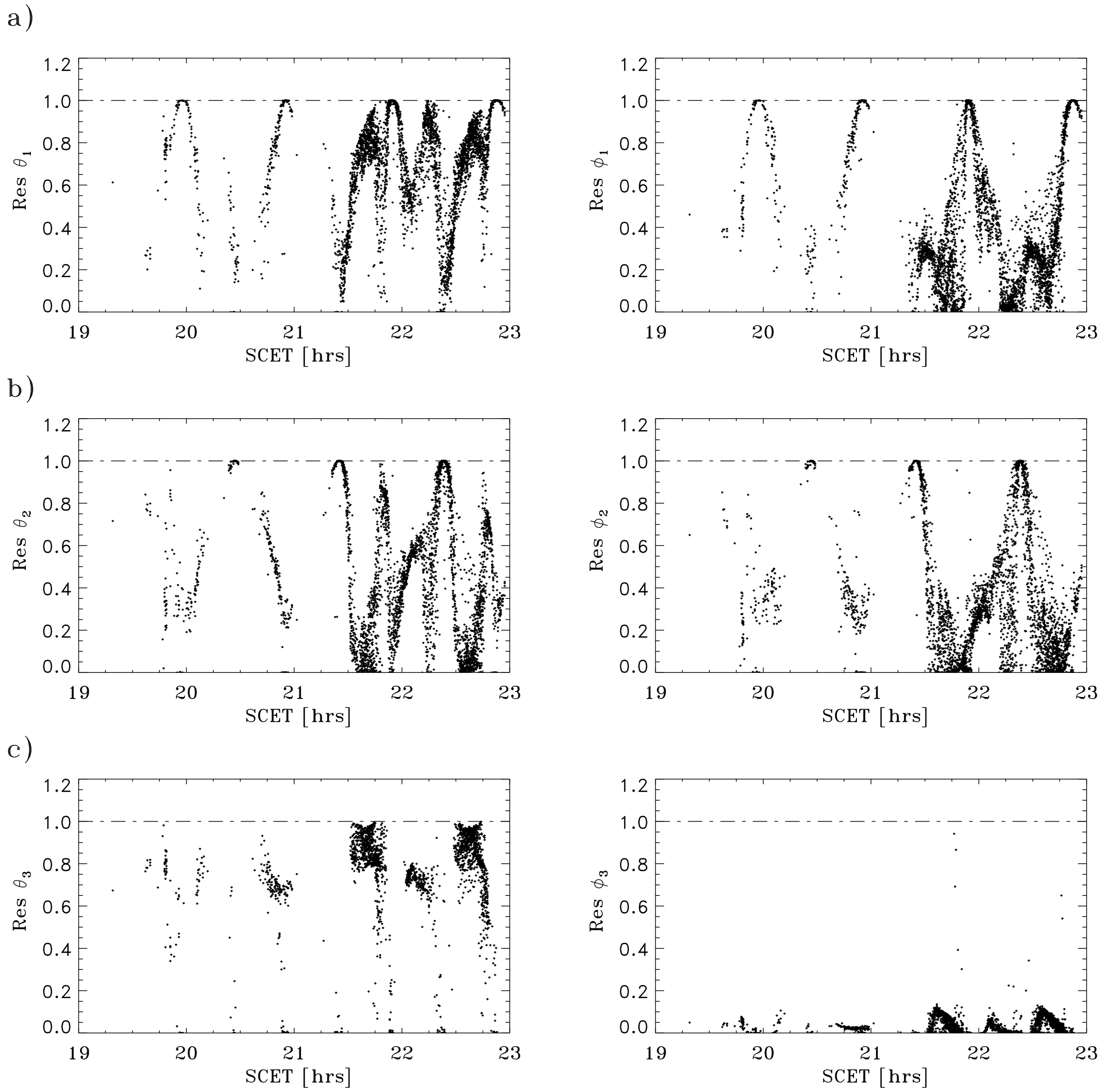

Figure 3: Parameter resolution of the RPWS antenna system using voltage measurements of DOY 320. Panel a) shows the resolution of the u antenna, panel b) shows the resolution of the v antenna, and panel c) shows the resolution obtained for the w antenna.

as a function of spacecraft event time. The dashed line in each panel refers to the mean value of each parameter.

In Table 3 we summarize our results using 3 roll maneuvers. For reference we give the results obtained by rheometry as well as the number of measurements of each event indicating high parameter resolution (last column). For each relevant parameter we also give for reference the value of the standard deviation, σ. We further note that these calculations are related to elliptical polarization (obtained from the direction finding analysis, see above) and that we do not obtain good results for the events DOY 335/2000 and DOY 340/2000 for high parameter resolution. As it is seen from the table the computed

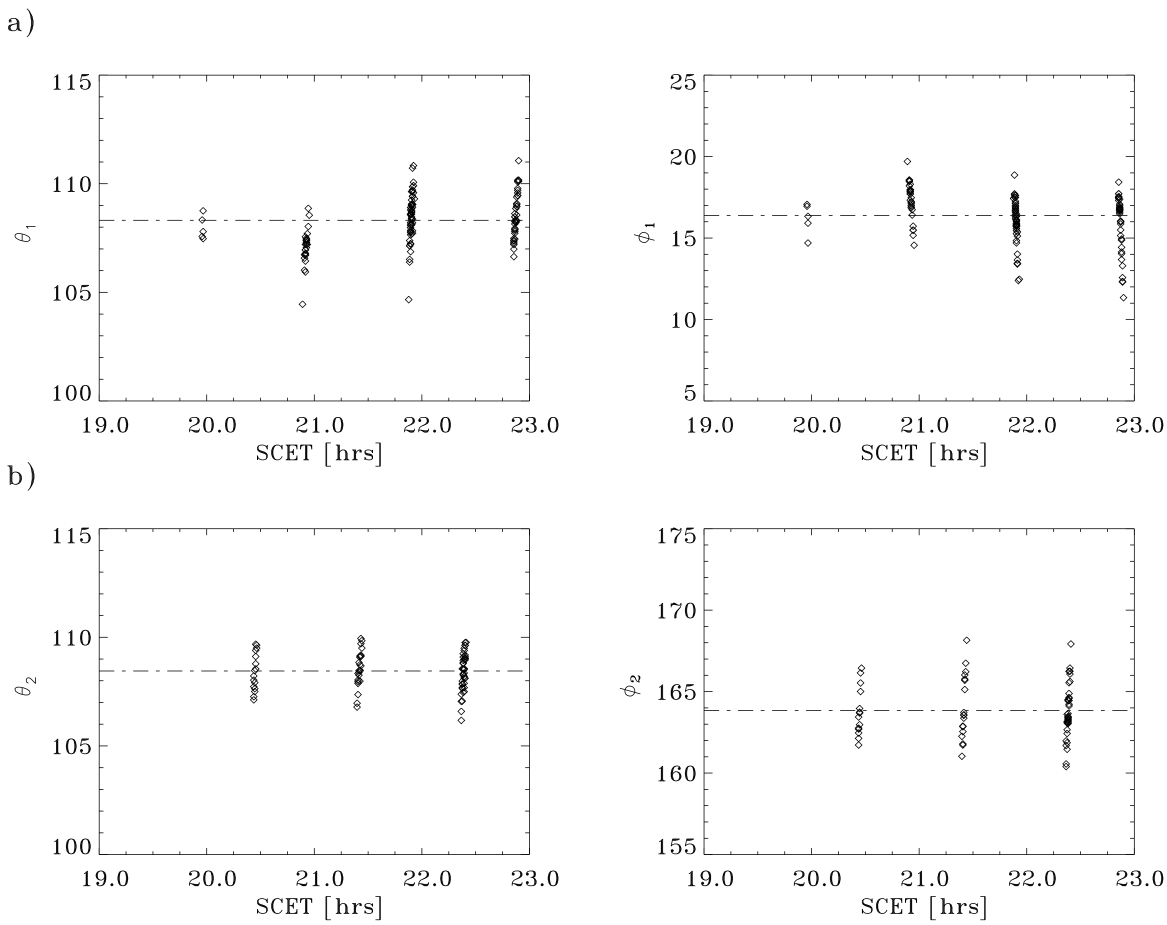

Figure 4: Directions of the u/v antennas for high parameter resolution.

co–latitude for all three events is approximately of the same range. The same is true for the azimuth of the antennas, except the value for DOY 330.

		Rheometry		In–flight calibration			
Event		θ	ϕ	θ (σ)	ϕ (σ)	Polarization	Number
320	u	107.9	16.5	108.32 (1.83)	16.38 (2.26)	Q=0, U=−0.3	131/120
	v	107.3	162.7	108.45 (0.84)	163.84 (1.70)	V=0.9	82/69
325	u	107.9	16.5	106.85 (3.40)	16.2 (4.75)	Q=0, U=−0.3	34/32
	v	107.3	162.7	108.10 (3.44)	165.43 (5.01)	V=0.9	8/7
330	u	107.9	16.5	107.97 (2.47)	15.77 (4.75)	Q=0, U=0.1	9/9
	v	107.3	162.7	107.49 (2.88)	192.77 (11.3)	V=0.99	7/6

Table 3: Co–latitude and azimuth of the u/v antennas for high parameter resolution, i.e., 99.9%, and for elliptical polarization.

Last we calculate the co–latitude and azimuth angles of the u/v antennas assuming a circular wave polarization (Q=0, U=0, V=1). The result is shown in Table 4. It can be seen that the results are close to those of Table 3!

Event		Rheometry θ	Rheometry ϕ	In–flight calibration θ (σ)	In–flight calibration ϕ (σ)	Polarization	Number
320	u	107.9	16.5	107.95 (0.93)	16.25 (1.61)	Q=0.0, U=0.0	152/154
	v	107.3	162.7	108.19 (0.75)	164.02 (1.54)	V=1.0	80/81

Table 4: Co–latitude and azimuth of the u/v antennas for high parameter resolution, i.e., 99.9%*, and for circular polarization.*

4 Summary and conclusions

In this report we have shown first results of the calibration of the Cassini RPWS antennas using Jovian radio emissions. We obtained the co–latitude and azimuth angles of the u/v antennas via roll maneuvers of the spacecraft around its x–axis done in November 2000. Our results are in good agreement with those of rheometry. Future activities include the calibration of the w antenna using roll maneuvers of Cassini done in the beginning of 2001. Finally we would like to implement our results as input parameters to compute the length of the antennas, h_1, h_2, and h_3, followed by an error analysis based on bayesian statistics [Ladreiter et al., 1998].

5 References

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