

WIRE–GRID MODELING OF CASSINI SPACECRAFT FOR THE DETERMINATION OF EFFECTIVE ANTENNA LENGTH VECTORS OF THE RPWS ANTENNAS

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Abstract

The Cassini RPWS (Radio and Plasma Wave Science) antenna system consists of three non-coplanar 10 m long monopoles. With this configuration the RPWS experiment is capable to perform a direction finding of incoming radio waves and to determine the four Stokes parameters. For this procedure it is necessary to know the so-called effective antenna length vectors, which describe the reception properties of the antenna system. Several methods have been used to determine these vectors. Although numerical calculations with a wire-grid model have already been performed, it was the aim of this work to calculate a more realistic and detailed wire-grid to determine the influence of several parts of the Cassini spacecraft like the tanks, the RTGs (Radio Thermonuclear Generators) and their shades, the Experimental Platform, the CDA (Cosmic Dust Analyzer), the Huygens Probe (HP) mounting and the HP itself, and the magnetometer boom (MB). The results are in good agreement with those found by the method of rheometry and the recent in-flight calibration of the RPWS antennas.

1 Introduction

For the description of the radiation of complicated antenna systems it is convenient to use an effective antenna length vector \vec{h}_{eff} , which can be calculated with the following integral [Macher, 1997]:

$$\vec{h}_{eff} = \frac{1}{I} \int \vec{J}(\vec{r}) e^{-i\vec{k}\vec{r}} dV = \frac{1}{I} \oint \vec{J}_F(\vec{r}) e^{-i\vec{k}\vec{r}} dF \quad (1)$$

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with I as feeding current, \vec{k} as wave vector, \vec{r} as coordinates of antenna elements, \vec{J} as current density (volume), dV as volume element, \vec{J}_F as surface current density and dF as surface area element.

For wavelengths greatly exceeding the dimensions of the spacecraft the imaginary part of the effective antenna length vector can be neglected and \vec{h}_{eff} can be calculated with the simpler equation (2):

$$\vec{k}\vec{r} \ll 1 \quad \vec{h}_{eff} = \frac{1}{I} \oint \vec{J}_F dF. \quad (2)$$

Due to the influence of the metallic spacecraft body \vec{h}_{eff} significantly deviates from the direction of the physical antenna rod. The clue of the introduction of effective antenna length vectors is that the voltage V received from an incident electromagnetic wave at the open antenna terminals can easily be expressed by:

$$V = \vec{E} \cdot \vec{h}_{eff}, \quad (3)$$

where \vec{E} is the electric field strength. If \vec{h}_{eff} is known and if 3 voltages for 3 non-coplanar antennas are measured, it is possible to derive the direction and polarization of the incoming radio wave.

2 Methods for the determination of effective antenna length vectors

The two methods, rheometry and in-flight calibration, are mainly based on equation (3). In the rheometry method a 1:30 down-scaled Cassini spacecraft model, which was made of brass and gold plated, was immersed into a homogeneous electric field \vec{E} generated by two parallel plates of a capacitor within a water-filled tank [Rucker et al., 1996]. Measuring the voltages V between one antenna and the spacecraft body while rotating the model will give zero response when \vec{h}_{eff} is orthogonal to \vec{E} according to equation (3). The same principle was used for the in-flight calibration during the Cassini Jupiter flyby, where radio waves originating from Jupiter have been measured during spacecraft roll maneuvers [Vogl et al., 2001a].

Regarding numerical antenna simulations usually the mathematical method of moments [Harrington, 1968] is applied to solve the EFIE and MFIE (electric and magnetic field integral equations) to gain the surface currents necessary for the calculation of \vec{h}_{eff} according to equation (1). There are different numerical codes available to solve the corresponding matrix equations.

The first wire-grid modeling of the Cassini spacecraft for numerical calculation was done a few years ago [Rucker et al., 1997] and the so-called MASAP (Modified Antenna Scattering Analysis Program) code was used. Figure 1 gives a sketch of this wire-grid (left) and of the rheometry model (right) and it also shows the Cassini spacecraft coordinate system which is usually stressed and used throughout this paper. Note that the +z-direction points towards the Lower Equipment Module and not towards the High Gain Antenna (HGA), which is in the -z-direction. The +y-direction is the direction of the magnetometer boom (MB), the +x-axis points to the Experimental Platform and the -x-direction

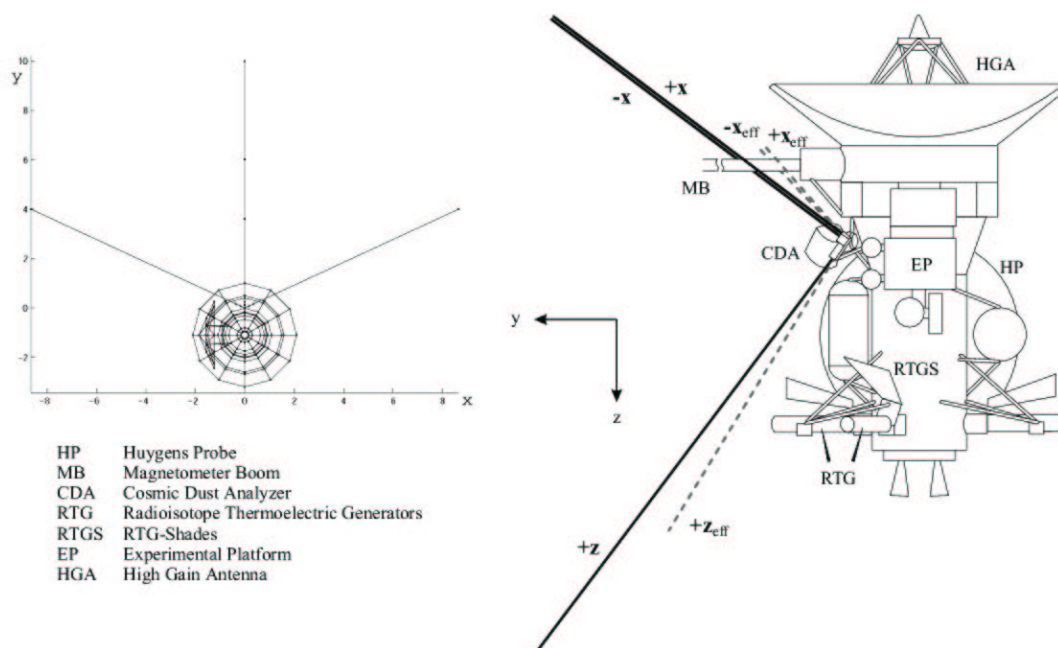


Figure 1: Sketch of wire-grid used for MASAP calculations and rheometry model. The origin of the Cassini model coordinate system is the point where the 3 RPWS antennas meet. Angle ϑ is the colatitude counted from the $+z$ -axis towards the xy -plane and φ is the azimuth counted from $+x$ towards the $+y$ -axis, as in any regular spherical coordinate system.

Table 1: Directions of physical antennas and effective antenna length vectors \vec{h}_{eff} of the Cassini RPWS antennas by rheometry measurement and MASAP numerical simulations for three different antenna modes. Results with Huygens Probe (HP) on and off [Rucker et al., 1997]. Angles ϑ and φ are the azimuth and colatitude in degrees, respectively.

Antenna Mode	Physical antennas		Rheometry \vec{h}_{eff} HP on		Rheometry \vec{h}_{eff} HP off		MASAP \vec{h}_{eff} HP on		MASAP \vec{h}_{eff} HP off	
	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ
w	37.0	90.0	31.4	91.2	30.8	92.9	29.0	83.5	28.0	85.0
u	107.5	24.8	107.9	16.5	107.6	16.3	106.5	14.5	104.5	14.5
v	107.5	155.2	107.3	162.7	106.4	163.5	106.5	161.0	106.0	162.0

to the Huygens Probe (HP). The dashed lines in Figure 1 at the rheometry model show the effective antenna axes indicating their deviation from the physical RPWS antenna rods (drawn as solid lines and not in scale). The corresponding angles (colatitude ϑ and azimuth φ) for the 3 different physical antennas u , v and w (former called $+x$, $-x$ and $+z$ -antenna) and the effective antenna length vectors for the rheometry method and the numerical MASAP calculations are given in Table 1. Although the results from the two methods rheometry and MASAP are quite in good agreement with each other, we wanted

to construct a more detailed wire-grid by including tanks, RTGs, the Experimental Platform, the CDA, a more realistic MB and the HP to find out, which elements have a great influence on the direction of the effective antenna length vectors and which have not. Table 1 also shows that the values for the azimuth angles $\varphi = 83.5^\circ$ and $\varphi = 85.0^\circ$ calculated with MASAP for the w -antenna mode are not satisfying. The wire-grid for the MASAP calculation with HP off is completely symmetric with regard to the RPWS antennas, hence the azimuth of the w -antenna mode should be close to $\varphi = 90.0^\circ$.

3 Basic concept of MATLAB-ASAP calculations

Our calculations were done with the so-called ASAP (Antenna Scatterers Analysis Program) code, which is freely available at the Internet. It is possible to download the executable program or even the Fortran source code from the webpage <http://soli.inav.net/~rlcross/asap/index.html>.

The original version of this program was developed by Richmond [1974] at the Department of Electrical Engineering of the Ohio State University Electro Science Laboratory. Later it was extended and modified by McCormack, who authored his master's thesis [McCormack, 1974] while he was at the Naval Postgraduate School. Information about ASAP and the source code was collected and published at the Internet by R. L. Cross. For the usage of ASAP one has to create an input file consisting of several input parameters. For the Cassini calculations we used the following parameters:

- **Geometry matrix:** It consists of the three dimensional coordinates of the nodes of the wire-grid model.
- **Description matrix:** It defines which nodes are connected by a thin wire segment.
- **Wire:** A conductivity of 10 MSie/m (or Mmhos/m), which is the conductivity of plain steel, was chosen. Variations of the conductivity by factors of 1/100 and 100 showed no significant influence on the directions of the effective antenna length vectors. The conductivity of the wire must greatly exceed the conductivity of the ambient medium, where free space was chosen. The wire radius has to be the same for the whole wire-grid and was fixed with 2 mm.
- **Frequency:** The requirement to keep the imaginary part of the effective antenna length vector small compared to its real part needs a frequency $f < 5$ MHz. A standard frequency of 500 kHz was chosen.
- **Feed Point:** We worked with only one feed point on one of the 3 RPWS antennas (w , u , v) located 20 cm away from the junction of the 3 antennas. We calculated only the w , u and v -antenna modes and no other possible antenna modes like the dipole mode for example. An input voltage of 10 V was chosen, so our antenna is actually emitting radio waves but due to the Reciprocal Theorem we directly get the effective antenna length vectors for a receiving antenna.

These input parameters have to be carefully checked to fulfill some ASAP-restrictions concerning the dimensions of the wavelength, the wire radius and the length of the longest and shortest wire segments. One important restriction is that the shortest segment has to be greater than 60 times the wire radius, which means that our minimum segment length is 12 cm. This thin wire assumption has to be fulfilled to get correct results from ASAP. Another restriction is that all angles between all wire segments at all nodes have to be $> 30^\circ$. The checking of the wire-grid with regard to these restrictions and the calculations of the effective antenna length vectors were done with MATLAB programs. In recent years we have developed a so-called MATLAB-ASAP toolbox consisting of several MATLAB programs for the handling and creation of wire-grids, for the plotting of grids, power patterns or currents and for the calculation of physical antenna characteristics like input or radiating powers, gains, front-back-ratios, electric fields, effective antenna length vectors, input impedances and others. ASAP is only used to calculate the currents on the wire-grid and the result is transferred to the MATLAB environment for further calculations.

4 Results

4.1 Adding spacecraft elements

We started our calculations with a wire-grid similar to that used for the MASAP calculation (HP off), consisting of the plain spacecraft (s/c) body with a simple line as magnetometer boom and the 3 intersecting RPWS antennas, which is also shown in Figure 2(a). This was our basic wire-grid to which we added further s/c parts. First we added elements which did not disturb the symmetry with regard to the 3 RPWS antennas. These elements are the two tanks, i.e. the cylindrical helium tank and the spherical monopropellant tank, both shown in a sketch in Figure 2(b). The results of our calculations (see Table 2) show that the symmetry of the effective antenna length vectors is preserved with our symmetric model, i.e. the azimuth φ for the w -antenna mode is 90° and the colatitudes ϑ for the u and v -antenna mode are the same. The influence of both tanks on the direction of the effective antenna length vectors is below 1° for all antenna modes.

The next steps comprised the addition of the RTGs and their shades (RTGs), the Experimental Platform (Exp) and the Huygens Probe mounting (HPm), which is the metallic ring remaining on the Cassini spacecraft body after the release of the Huygens Probe. Again Table 2 shows the result with all those elements added and the influence is of course bigger than for the tanks only.

In a third step we included the Cosmic Dust Analyzer (CDA), which is shown in Figure 2(c). The CDA can be rotated and in some positions it gets quite close to the v -RPWS antenna. We calculated the effective antenna length vectors for three different CDA positions but there was practically no influence. In Table 2 we list only the result for the default 0° position and the deviations of the effective antenna length vectors due to the CDA is also marginal.

As a last step we added the Huygens Probe (HP), as it is shown in detail in Figure 2(d).

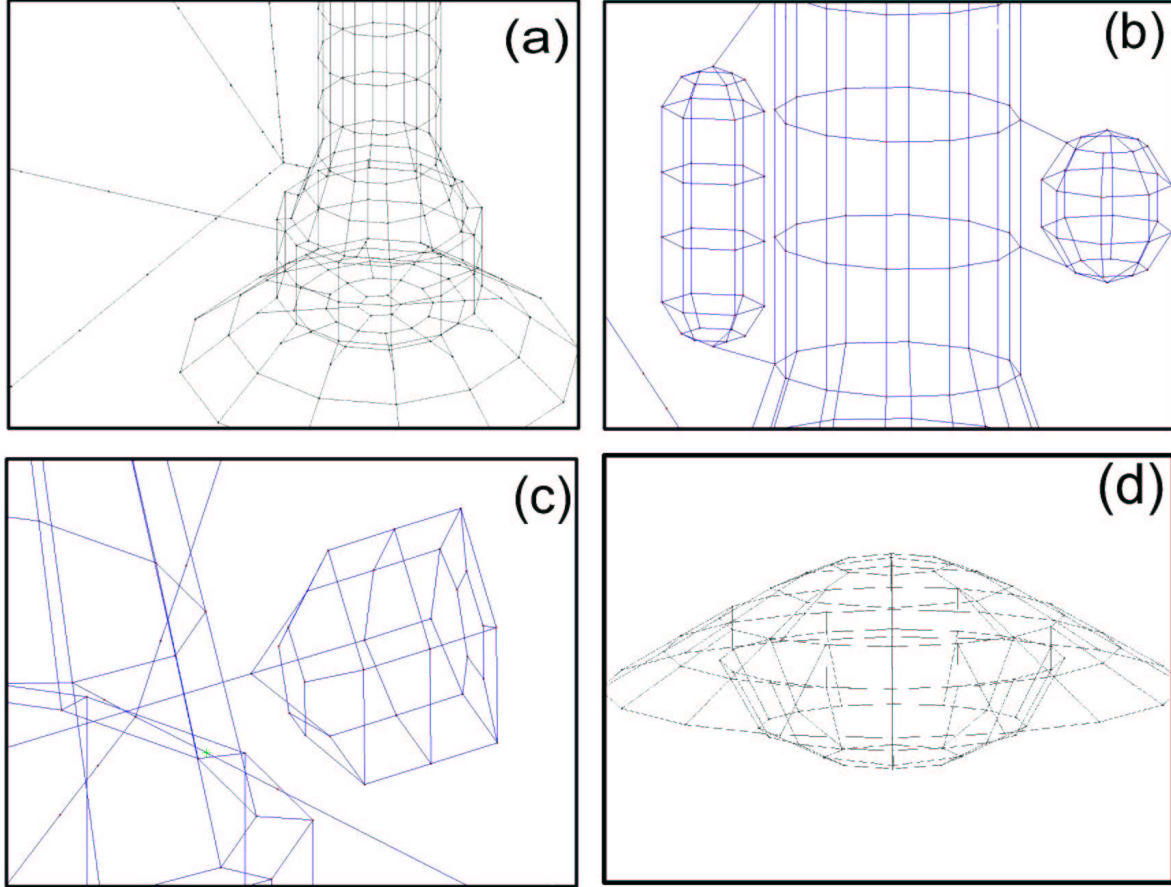


Figure 2: Sketch of four Cassini wire-grids showing the plain s/c body with the 3 RPWS antennas and the magnetometer boom (a), the tanks (cylindrical helium tank and spherical monopropellant tank) (b), the Cosmic Dust Analyzer (CDA) (c) and the Huygens Probe (d).

The results in Table 2 show that the HP on the $-x$ side compensates the influence of the Experimental Platform on the $+x$ side and the effective antenna length vectors are nearly symmetric again.

Of course it would be possible to add some more smaller elements like the thruster clusters, the main and backup engines, the low gain antennas (LGA) or the RPWS search coil, but as the CDA has shown one can expect only a marginal influence on the direction of the effective antenna length vectors by such small elements.

4.2 Important wire-grid modifications

So far the magnetometer boom (MB) has been modeled as a simple line and a more realistic design would be desirable. Figure 3 shows the modification from the simple design 1 to the more realistic design 2 with a triangle shaped cross-section. Table 3 shows that there is a massive influence of the MB design on the directions of the effective

Table 2: Directions of effective antenna length vectors \vec{h}_{eff} of Cassini RPWS antennas for three different antenna modes and 5 different wire-grid models. Structures are added onto the previous configuration to the left. *s/c* denotes the spacecraft, *RTGs* are the Radio Thermonuclear Generators (+their shades), *Exp* is the Experimental Platform, *HPm* the Huygens Probe mounting and *HP* the Huygens Probe itself. *CDA* stands for Cosmic Dust Analyzer in 0° position. Angles ϑ and φ are the azimuth and colatitude in degrees, respectively.

Antenna Mode	"plain" s/c body		tanks added		RTGs+Exp +HPm added		CDA 0° added		HP added	
	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ
<i>w</i>	26.5	90.0	27.3	90.0	30.9	91.9	30.8	91.7	31.6	90.1
<i>u</i>	106.0	14.0	106.3	14.5	108.6	17.1	108.6	17.1	108.8	17.4
<i>v</i>	106.0	166.0	106.3	165.5	107.9	163.8	108.0	163.8	108.8	162.8

antenna length vectors, especially on the colatitude ϑ of the *w*-mode and on the azimuth angles φ of the *u* and *v*-antenna modes, which are tilted by 5° to 6° towards the *s/c* body when changing from MB design 1 to design 2. For illustration we add the values for a fictional spacecraft without the MB to underline the important influence of the MB on the directions of the effective antenna length vectors. Although MB design 2 is more realistic, the agreement with rheometry is not so good as with MB design 1.

Figure 3 also shows another important modification: So far all three RPWS antennas

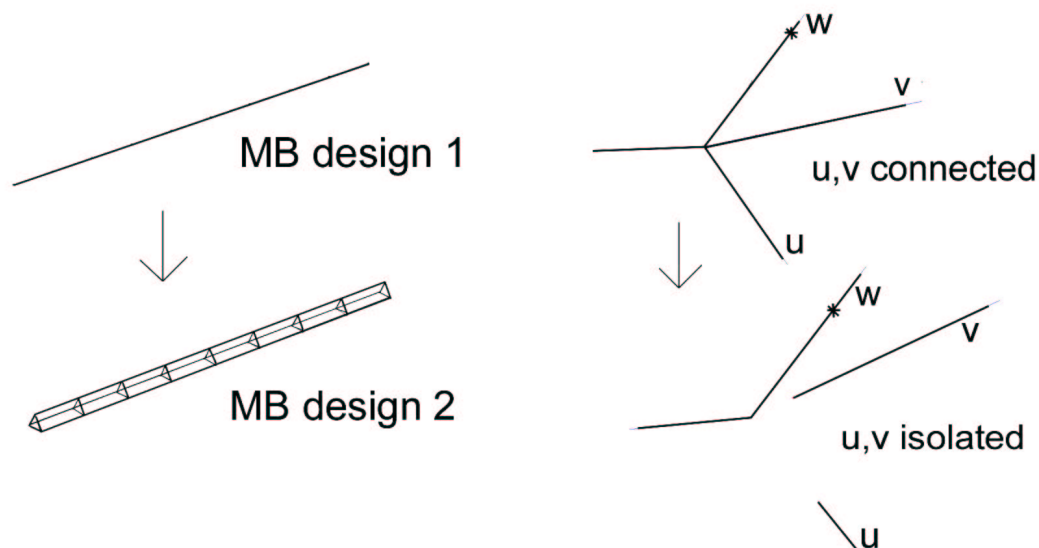


Figure 3: Left: Two different designs of the magnetometer boom (MB) as a simple line or a more realistic design with a triangle shaped cross-section. Right: Illustration of antennas connected to and isolated from the spacecraft body. Here the feed point is on the *w*-antenna.

met at one point, and on one of them the feed point was located 20 cm away from the

Table 3: Directions of effective antenna length vectors \vec{h}_{eff} of Cassini RPWS antennas for three different antenna modes. Angles ϑ and φ are the azimuth and colatitude in degrees, respectively. MB is the magnetometer boom (design 1 and 2, see Figure 3). Ant. con. and Ant. iso. means that the two non voltage-driven antennas are connected or isolated with regard to the s/c body. All s/c elements (tanks, RTGs, Exp, CDA, HP) are added.

Antenna Mode	no MB		MB design 1		MB design 2		MB design 1		MB design 2	
	Ant. con.		Ant. con.		Ant. con.		Ant. iso.		Ant. iso.	
	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ	ϑ	φ
w	38.1	90.1	31.6	90.1	26.2	90.1	36.7	89.5	29.6	89.5
u	109.2	24.0	108.8	17.4	108.3	11.9	106.7	23.5	106.4	16.0
v	109.2	156.3	108.8	162.8	108.3	168.3	107.0	156.7	106.6	164.2

intersection. This means that while one antenna is driven versus the spacecraft body the two other antennas are connected to the s/c. Due to the fact that the antennas have a certain input impedance it is more realistic to isolate these two antennas from the spacecraft body. Also in our rheometry model the potential drop from one antenna to the s/c was measured while the other two antennas were isolated from the s/c. The last two columns of Table 3 show the effect of isolating the respective two antennas from the s/c body. Note that similar to the MB design this modification has also a big influence on the colatitude ϑ of the w -mode and on the azimuth angles φ of the u and v -antenna modes. But on the contrary to the MB design the effective antenna length vectors are tilted away from the s/c body when changing from connected to isolated antennas. So both modifications have a big but contrary influence and the results for MB design 2 with isolated antennas are again close to rheometry results.

5 Conclusion

Figure 4 shows our final Cassini-Huygens wire-grid design with all elements added, the more realistic magnetometer boom design and the respective antennas are isolated from the spacecraft (which can hardly be seen in Figure 4).

In the final Table 4 we compare the results of rheometry with the results of our new calculations with and without the Huygens Probe. As it can be seen there is quite a good agreement and the deviations are smaller than 2° for the majority of angles in the various antenna modes. Additionally first results of the in-flight calibration [Vogl et al., 2001a] are listed in Table 4. This Jupiter-flyby in-flight calibration was of course performed with the Huygens Probe (HP) attached to the spacecraft and if no more in-flight calibration without HP will be done, the results of rheometry and numerical calculations with the HP off will get quite important. Removal of the HP changes the colatitude angles ϑ for rheometry by -0.6° , -0.3° , -0.9° in the respective antenna modes and the azimuth angles φ by $+1.7^\circ$, -0.2° , $+0.8^\circ$. For our numerical calculation the respective changes are -1.2° , -0.2° , -0.9° for colatitude angles and $+2.2^\circ$, -0.7° , $+1.4^\circ$ for azimuth angles, which is in good agreement with the rheometry result.

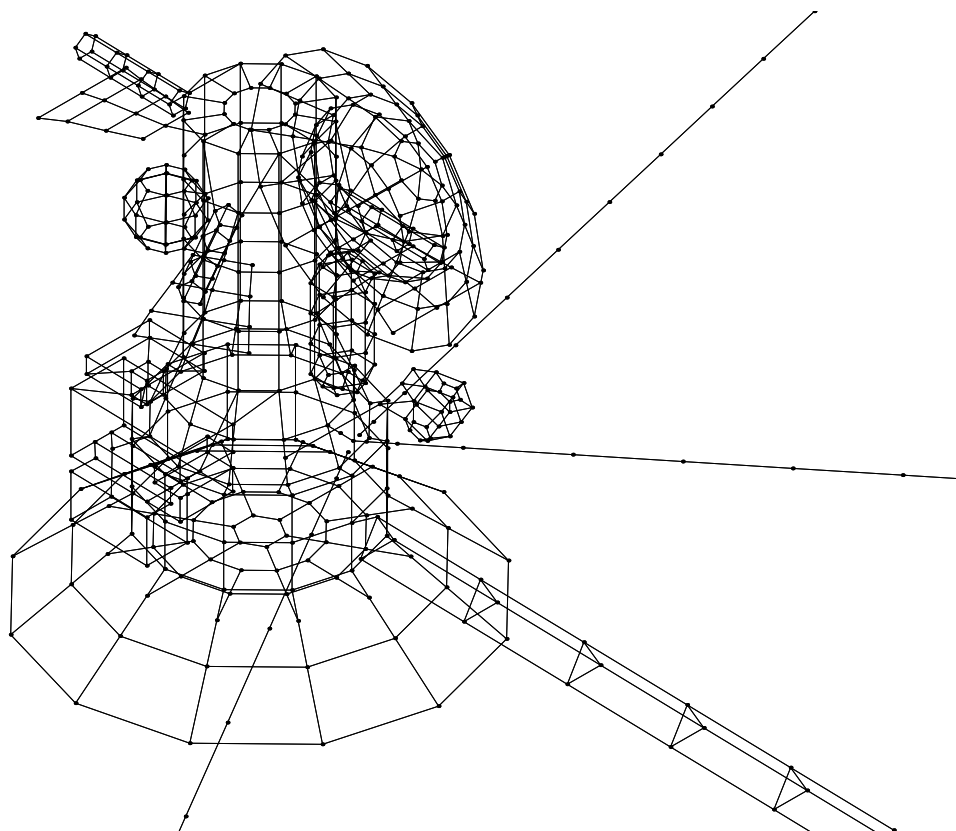


Figure 4: Sketch of the final wire-grid design for Cassini-Huygens with more than 600 nodes and 1000 segments.

Table 4: Directions of effective antenna length vectors \vec{h}_{eff} of Cassini RPWS antennas by rheometry measurement, our new numerical calculations (this paper) and in-flight calibration for three different antenna modes [Rucker et al., 1997; Vogl et al., 2001a (Event 320)]. Results with Huygens Probe (HP) on and off. Angles ϑ and φ are the azimuth and colatitude in degrees, respectively.

Antenna Mode	Rheometry		Rheometry		New calc.		New calc.		in-flight cal.	
	\vec{h}_{eff} ϑ	HP on φ	\vec{h}_{eff} ϑ	HP off φ	\vec{h}_{eff} ϑ	HP on φ	\vec{h}_{eff} ϑ	HP off φ	$(\vec{h}_{eff}$ ϑ	HP on) φ
w	31.4	91.2	30.8	92.9	29.6	89.5	28.4	91.7	—	—
u	107.9	16.5	107.6	16.3	106.4	16.0	106.2	15.3	108.3	16.4
v	107.3	162.7	106.4	163.5	106.6	164.2	105.7	165.6	108.5	163.8

Rucker et al. [1996] estimates the results of rheometry to be accurate within 2° , and Vogl et al. [2001a] give standard deviations of the angles for the u and v antenna modes ranging from 0.8° to 2.3° (Event 320). In our numerical calculation it is not so easy to perform an error analysis: On the one hand there is a small error of the numerical code

ASAP itself and the wire-grid is of course only a model, but on the other hand the results of the calculation are very stable with regard to small changes of the wire radius, addition or removal of wire segments or different modeling of certain elements. For example we also modeled tanks with much denser grids with more nodes and segments than shown in Figure 2(b), but there was practically no change in the direction of the effective antenna length vectors. So we would estimate the error of our calculations also to be about 2° . Our new Cassini wire-grid calculations have shown that

- the influence of tanks, the Experimental Platform, the CDA and the HP mounting is small (below 1° for one single part),
- the rotation of the CDA has no influence,
- the Huygens Probe, the RTGs (+shades) and especially the magnetometer boom and isolation of the RPWS antennas from the s/c body have a great influence on the directions of the effective antenna length vectors.

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