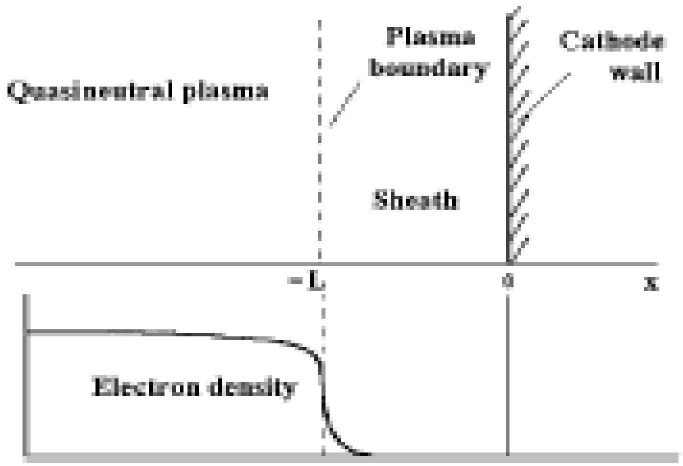
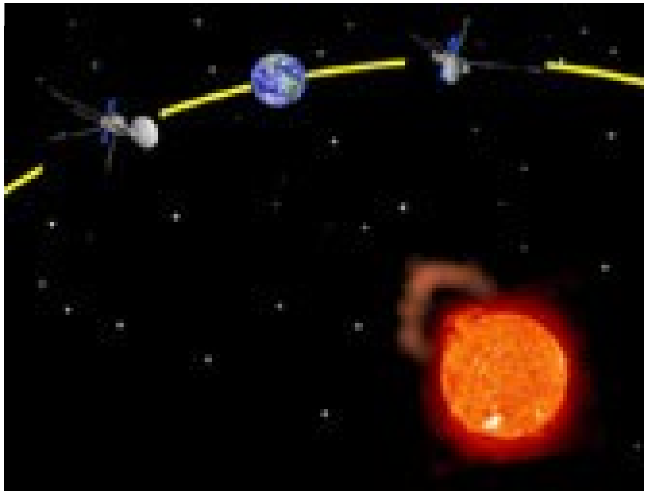
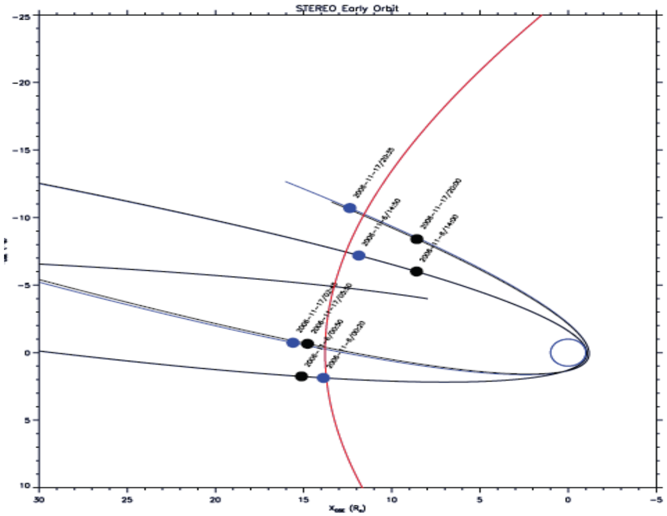
The Physics of the plasma sheath







The Physics of the plasma sheath

Basics

- The space is filled with space plasma.
- The plasma interacts with an object made of conducting material (spacecraft) which is immersed in the plasma.
- A boundary zone forms around the body.
- This boundary zone is called plasma sheath.

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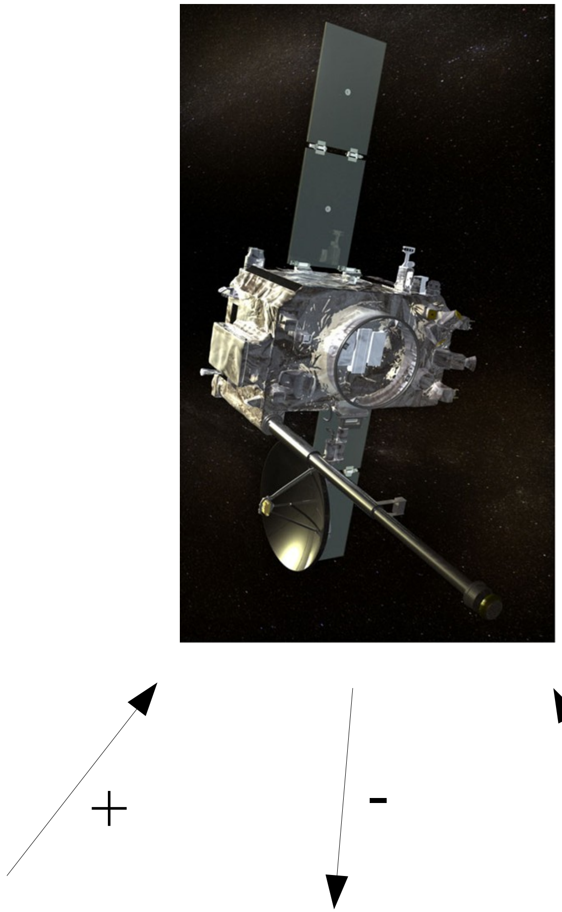
Basics

- 2 or 3 different currents flow to the spacecraft, depending on the environment.
- In a steady state condition the, sum of the currents must be zero.
- Depending on the magnitude of the photo-electron current, the spacecraft can be charged positively or negatively.
- Depending on the charging, there are two different forms of the sheath possible.



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Negatively charged spacecraft

- No illumination --> only thermal electron- and ion-current.
- At comparable temperatures the mean speed of the electrons will be higher.
- --> more electrons hit the surface in a given time interval.
- --> the S/C will be charged negatively.
- --> the negative charge of the S/C pushes away the mobile electrons and attracts the ions.
- --> an electron depletion zone forms around the S/C
- --> the sheath thickness and S/C potential will adjust such that the currents have the same magnitude

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Positively charged spacecraft

- The number of photo-electrons exceeds the number of thermal electrons.
- -->The body builds a positive charge such that the number of photoelectrons reaching the plasma is roughly equal to the number of thermal electrons impacting on the surface.
- All other photo-electrons are unable to cross the potential difference and fall back to the surface.
- These photoelectrons form an electron sheath.
- They do not contribute to the photo-electron current.

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The currents

- The currents can be estimated.
- All thermal electrons reach the surface, while only photoelectrons with a certain minimum energy.
- The photoelectrons are roughly Maxwell distributed.[Grard 1973]
- i_{ph} ...current density at the surface.
- A_{rel}...relative illuminated area cross section.
- The potential of the spacecraft can be deduced by equating thermal and photo-electron current.

$$I_e = -en_e dl\pi\sqrt{\frac{\kappa T_e}{2\pi m_e}}$$

$$I_{ph} = A_{rel} i_{ph} l d e^{-\frac{eV}{\kappa T_{ph}}}$$

$$V = -\frac{\kappa T_{ph}}{e}\ln\left[\frac{en_e\pi}{A_{rel} i_{ph}}\sqrt{\frac{\kappa T_e}{2\pi m_e}}\right]$$

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The densities

- The photo-electron density at the surface can be found by using $\mathbf{j} = \bar{\mathbf{v}} n q$.
- Equilibrium: Produced electrons=impacting electrons (ignoring ions)
- A possible way to estimate the sheath thickness.

$$n_{ph}(0) = \frac{A_{rel} i_{ph}}{\pi \bar{v}_{ph}(0) e}$$

$$n_{e,tot}(0) = \frac{2 A_{rel} i_{ph}}{\pi \bar{v}_{ph}(0) e}$$

$$\delta \sim \lambda_{ph} = \sqrt{\frac{\epsilon_0 \kappa T_{ph}}{n_{totph}(0) e^2}}$$

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The densities

- The distribution of the photo-electron density.
- The density of the thermal electrons can be derived as before.
- The heavy ions are assumed not to be influenced by the potential gradient.

$$n_{ph}(x) = 2n_{ph}(0)e^{-\frac{e(V-\phi(x))}{\kappa T_{ph}}}$$

$$n_e(x) = \frac{\bar{n}_e}{\sqrt{1 + \frac{2e\phi(x)}{m_e \bar{v}_e^2}}}$$

$$n_i(x) = \bar{n}_i$$

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The governing differential equation

- 1D flat surface approximation.

- Substitution of the densities results in a Poisson equation.

$$\frac{d^2\phi(x)}{dx^2} = -\frac{e}{\epsilon_0}\left(\bar{n}_i - n_{ph}(x) - n_e(x)\right)$$

Boundary Conditions

$$\begin{aligned} \phi(0) &= V \\ \phi(\infty) &= 0 \end{aligned}$$

$$\frac{d^2\phi(x)}{dx^2} - \frac{2en_{ph}(0)}{\epsilon_0} e^{-\frac{e(V-\phi(x))}{\kappa T_{ph}}} - \frac{e\bar{n}_e}{\epsilon_0\sqrt{1+\frac{2e\phi(x)}{m_e\bar{v}_e^2}}} = -\frac{e\bar{n}_i}{\epsilon_0}$$

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The linearized equation

- Taylor expansion.
- Assuming quasi-neutrality.
- Only valid for small potential energies.

$$\frac{1}{\sqrt{1+\frac{2e\phi(x)}{m_e\bar{v}_e^2}}} \sim 1-\frac{2e\phi(x)}{m_e\bar{v}_e^2}$$

$$e^{\frac{e\phi(x)}{kT_{eph}}} \sim 1+\frac{e\phi(x)}{\kappa T_{ph}}$$

$$\frac{d^2\phi(x)}{dx^2}-\frac{2e^2}{\epsilon_0}\left(\frac{n_{ph}(0)}{\kappa T_{ph}}e^{-\frac{eV}{\kappa T_{ph}}}+\frac{\bar{n}_0}{m_e\bar{v}_e^2}\right)\phi(x)=\frac{2en_{ph}(0)}{\epsilon_0}e^{-\frac{eV}{\kappa T_{ph}}}$$

- The solution is the sum of an exponential function and a constant.
- Does not fulfill the boundary conditions.
- One can define the shielding length.

$$\lambda_{sh}=\left[\frac{2e^2}{\epsilon_0}\left(\frac{n_{ph}(0)}{\kappa T_{ph}}e^{-\frac{eV}{\kappa T_{ph}}}+\frac{\bar{n}_0}{m_e\bar{v}_e^2}\right)\right]^{-\frac{1}{2}}$$

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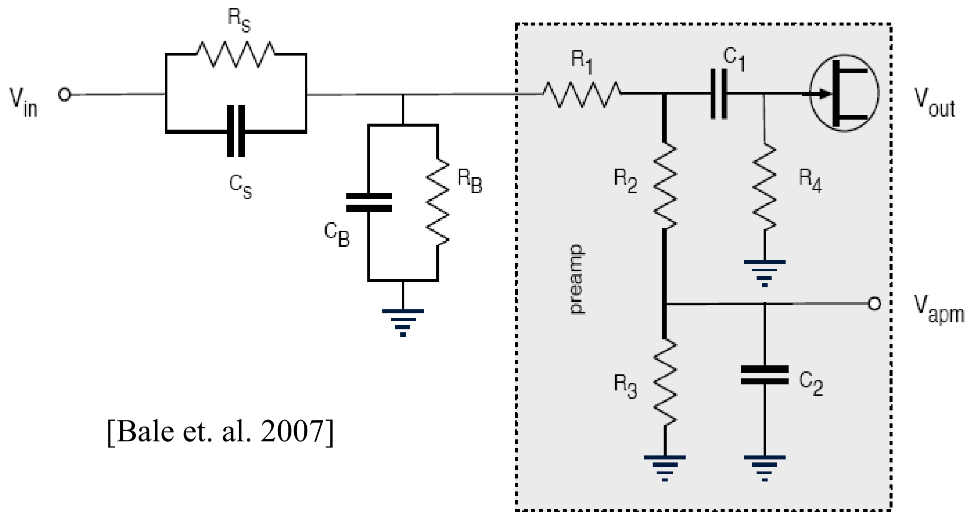
- Spacecraft antennas are usually coupled to the surrounding space plasma.
- The electromagnetic coupling can be modeled by a system of a resistance and a capacitance.
- In rarefied plasma the coupling can not take place without photoelectrons.
- The sheath thickness must not be larger than the antennas.



[Bale et. al. 2007]

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- The expressions for the positively charged spacecraft.
- ϵ_r is the relative impedance tensor which depends on the model used.
- Changes continuously along the sheath.
- As a first approximation the mean value could be used.

$$\boxed{R_s = \frac{\partial V}{\partial I}}$$

$$\boxed{R_s = -\frac{\kappa T_{ph}}{e I_{ph}}}$$

$$\boxed{C_s = l_a \frac{2\pi\epsilon_0\bar{\epsilon}_r}{\ln\left(\frac{\delta}{r_a}\right)}}$$

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Application

- STEREO operates in solar wind conditions at 1AU.
- The photo-electron production rate is higher than the thermal electron impact rate.
  --> positive charge.
- i_{ph}...10^{-4}Am^{-2} [Fahrleson 1967]
- A_{rel}...0.5
- l=6m
- d=1in (0.0254m) on average
- Mean energy of photo-electrons=1.5eV [Grard 1973]
- Mean energy of thermal electrons=10eV

$$I_{ph} = A_{rel} i_{ph} l d \sim 7.6 \cdot 10^{-6} A$$

$$I_e = -e n_e d \pi \sqrt{\frac{\kappa T_e}{2\pi m_e}} \sim -2 \cdot 10^{-7} A$$

- -->V=5.5V
- $\overline{n}_e$=10^6m^{-3}
- -->n_{ph}(0)=2x10^8m^{-3}
- -->2.5% of the photo-electrons reach the plasma.
- -->λ_{sh} =0.6m or 0.4m, depending on the method.

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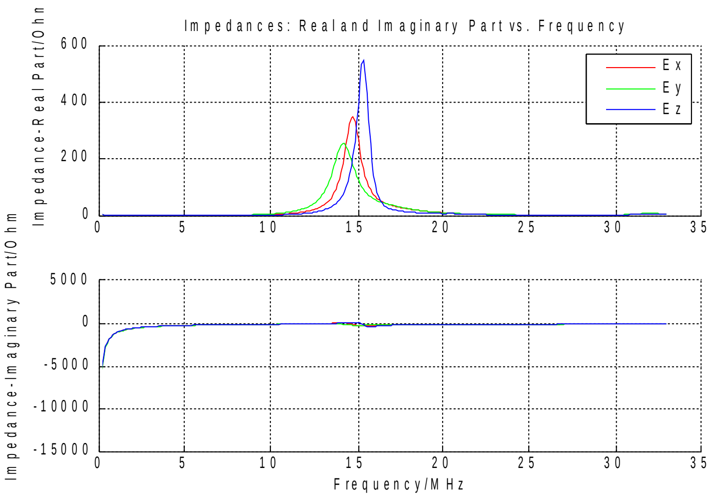
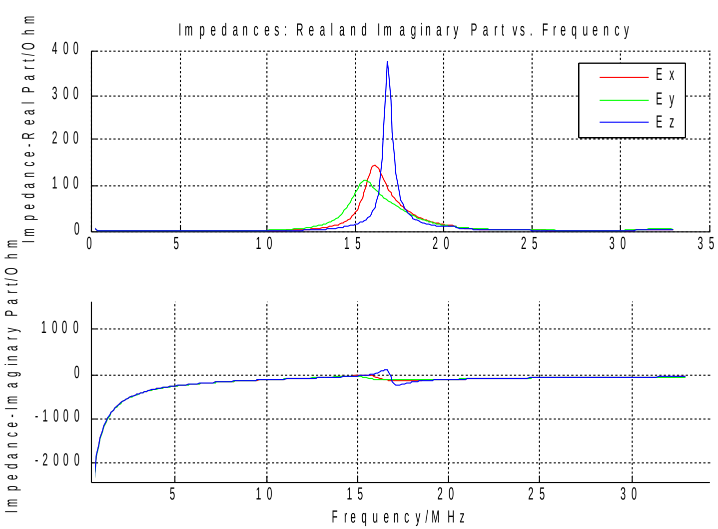
Application

- Using the appropriate equations, one finds:
  - $R_s = 0.2 M\Omega$
  - $C_s = 87 pF$
- Via these parameters the sheath can be included into the numerical antenna calibration (wire-grid).
- Computation of the impedances show that the inclusion of the sheath has an effect.





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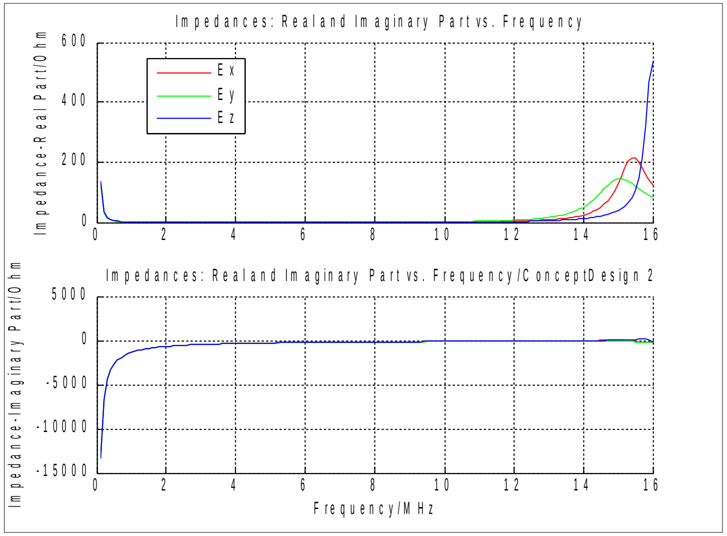
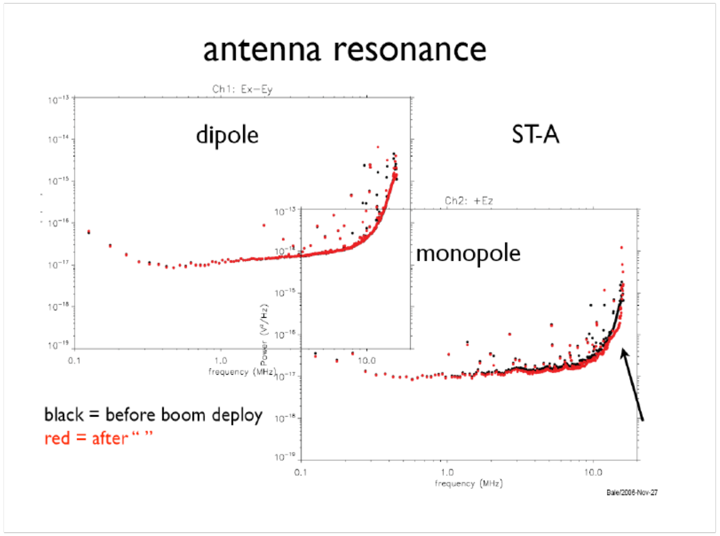
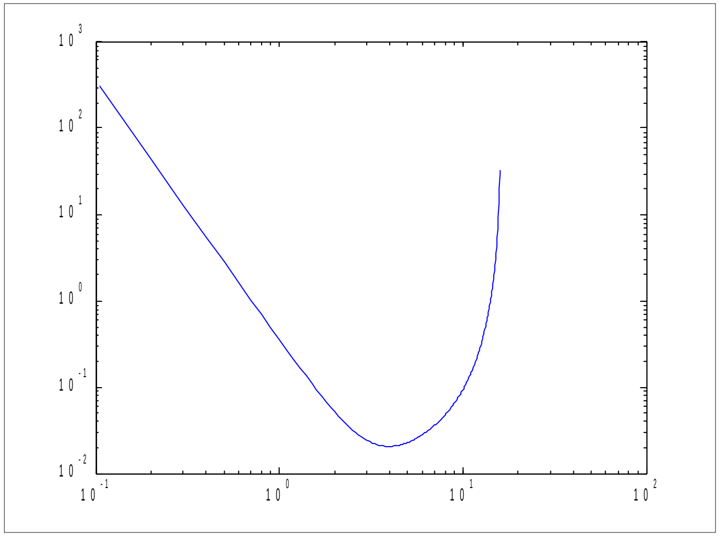
Application

- Comparing the location of the second resonance of antenna E_z with measured data shows that the inclusion of the sheath capacitance has a corrective effect.
- Further and more accurate data is needed to verify the model.







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Final Remarks

- The surface of a body immersed in space plasma interacts in a complicated way with the plasma.
- The body is charged negatively or positively and a sheath is formed.
- Models approximating the physics of the electron sheaths were derived and partly solved.
- Representing the sheath by a combination of resistivity and capacitance, the coupling of the antenna to the space plasma can be incorporated into the numerical antenna calibration.
- As an example, the STEREO/WAVES antennas were used.
- The results are promising, but we have to validate the models used.
- Many estimations have to be used in the models.
- A uniform sheath around the spacecraft has been assumed.
- The velocity of the spacecraft has been neglected.

Thank You for Your attention !