Kinetic simulations and regression inference of plasma environment parameters

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with contributions from

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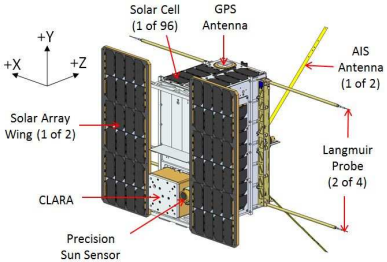
SPINE meeting
June 8 - 10, 2021

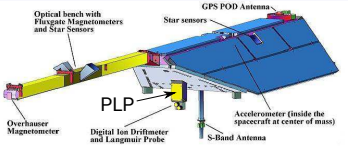
The problem

Proba-2

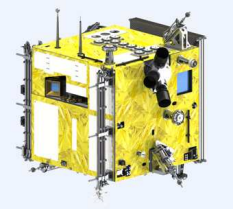


Norsat 1 & 2

- Many satellites carry Langmuir probes.
- Density and temperature are not measured directly.
- They are inferred from measured currents vs. voltages.



CHAMP satellite



China Seismo-electromagnetic Satellite

Common assumptions made in Theory

- $r \ll \lambda_D$, or $r \gg \lambda_D$,
- Stationary electrons
- Either $v_i \gg v_{i\,th}$ or $v_i \ll v_{i\,th}$
- $\vec{B} = 0$, or strongly magnetised plasma,
- collisionless, or strongly collisional plasma,
- Maxwellian background distribution
- For a cylindrical probe, $l \gg \lambda_D$
- Uniform plasma background, stationary or supersonic
- No nearby objects
- No photoelectron or secondary electron emission

Problem: Some of these assumptions are not satisfied.

Example analytic formulas: OML

Small spherical probe:

$V < 0$

$$I_{net} \simeq \pi n e a^2 v_{id} \left(1 - \frac{eV}{m v_{id}^2/2}\right)$$

if $v_{id} \gg v_{i\,th}$

$$I_{net} \simeq n e a^2 \sqrt{\frac{8\pi k T_i}{m_i}} \left(1 - \frac{eV}{kT_i}\right)$$

if $v_{id} \ll v_{i\,th}$
$|eV| > kT_i$

$V > 0$

$$I \simeq n e a^2 \sqrt{\frac{8\pi k T_e}{m_i}} \left(1 + \frac{eV}{kT_e}\right)$$

if $v_{ed} \ll v_{e\,th}$
$eV > kT_e$

Long thin cylindrical probe

$V > 0$

$$I_{net} \simeq -n_e e A \sqrt{\frac{kT_e}{2\pi m_e}} \left(1 + \frac{e(V_f + V_b)}{kT_e}\right)^{\beta},$$

if $v_{ed} \ll v_{e\,th}$
$eV > kT_e$

What are the alternatives?

To be practical, these options must:

- Be more accurate than analytic expression.
- Account for more physical processes and general conditions under which measurements are made, must be accounted for.
- Be fast, capable of inferring n, T, ..., with modest computing resources.

This rules out direct multi-physics 3D simulations, which would take too much computer resources and time.

Solution

- Construct *solution libraries* consisting of low level (L1B) measurements, with corresponding known plasma parameters.
- Use these libraries to train and validate inference models.

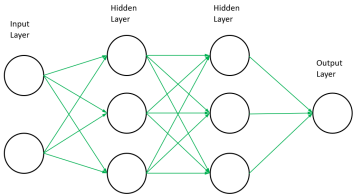
Options:

- Libraries constructed experimentally if accurate, validated data are available.
- *Synthetic data* made with simulations accounting for more physical processes and more realistic geometry than possible in theoretical models.

Regression

Interpolate physical plasma parameters (n_e, T_e, , V_S, ...) in a multivariate space of physical measurements (I_i).

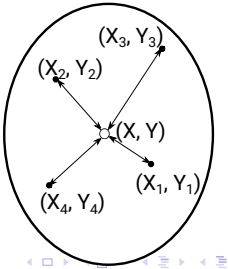
- Deep learning neural network.
  (Chalaturnyk, Marchand, Frontiers Phys. 2019)



- Radial basis functions (RBF).

$$\vec{Y} \simeq \sum_{i=1}^{N} a_i G\left(|\vec{X} - \vec{X}_i|\right)$$

$$\vec{Y}_j = \sum_{i=1}^{N} a_i G\left(|\vec{X}_j - \vec{X}_i|\right).$$



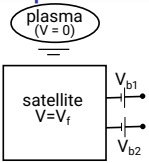
Two possible approaches with RBF

- Model 1: OML-like analytic, corrected with with multivariate regression.
- Model 2: Direct regression, no analytic bias.

In each case:

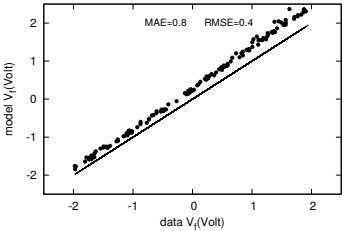
- Construct a data set with n-tuples of currents and corresponding plasma parameters (n_e, T_e, V_f, ...)
- Use regression to construct an inference model for selected parameters.
- Train with a subset of the solution library.
- Validate with the remaining subset.

Example 1 - fixed-bias spherical probes[1]

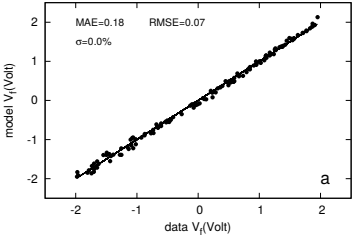


$$I = -ner^2\sqrt{\frac{8\pi kT_e}{m_e}}\left(1+\frac{e\left(V_f+V_b\right)}{kT_e}\right)$$

$$V_f + \frac{kT_e}{e} = \frac{V_{b1}I_2 - V_{b2}I_1}{I_1 - I_2}$$



OML alone



Combined OML RBF

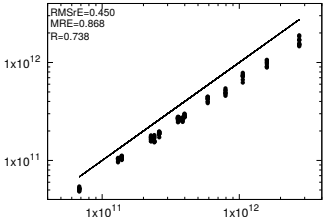
[1] Olowookere, Marchand, IEEE Trans. Plasma Sci. DOI: 10.1109/TPS.2020.3045366

Example 2 - Fixed-bias probes, $n_e/\sqrt{T_e}$[2]

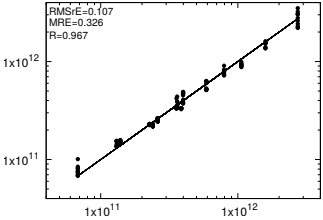
$$I = -ner^2\sqrt{\frac{8\pi kT_e}{m_e}}\left(1+\frac{e\left(V_f+V_b\right)}{kT_e}\right)$$

$$V_f + \frac{kT_e}{e} = \frac{V_{b1}I_2 - V_{b2}I_1}{I_1 - I_2}$$

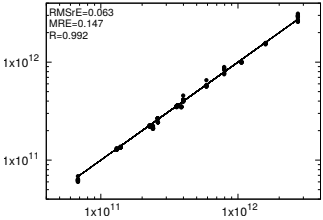
$$\frac{n}{\sqrt{T_{e\mathrm{V}}}} = \frac{1}{er^2}\sqrt{\frac{m_e}{8\pi e}}\left(\frac{I_1 - I_2}{V_{b2} - V_{b1}}\right)$$



OML alone



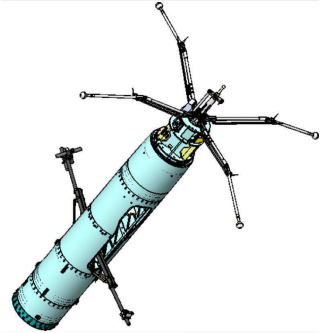
RBF alone



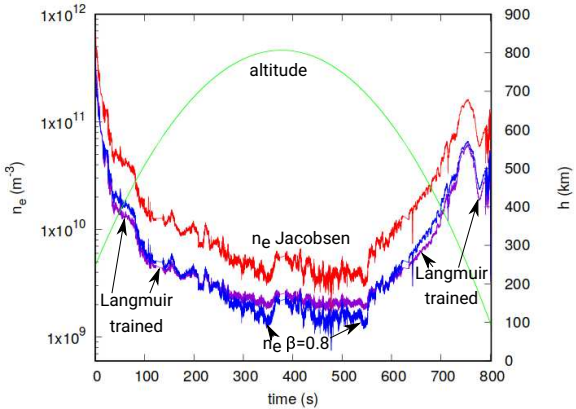
Combined OML-RBF

[2] Olowookere, Marchand, DOI: 10.1109/TPS.2021.3076806

Example 2 - Application to Visions-2 data



$$I_{net} \simeq -n_e e A \sqrt{\frac{kT_e}{2\pi m_e}} \left(1 + \frac{e(V_f + V_b)}{kT_e}\right)^{\beta},$$



Training with langmuirproject/langmuir github (S. Marholm)

Guthrie, et al., Measurement Science and Technology, accepted, 2021

Summary

- The century-old problem of inferring physical parameters from Langmuir probe measurements remains challenging.
- Are regression-based models trained with synthetic data from kinetic simulations, ready to be included among techniques used to infer plasma and spacecraft parameters from Langmuir probe measurements?
- Answer:

Summary

- The century-old problem of inferring physical parameters from Langmuir probe measurements remains challenging.
- Are regression-based models trained with synthetic data from kinetic simulations, ready to be included among techniques used to infer plasma and spacecraft parameters from Langmuir probe measurements?
- Answer: **Yes**.