MISSFIT Magneto-Ionization Spacecraft Shield for Interplanetary Travel

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Introduction

The MISSFIT research collaboration is a student-run, interdisciplinary research group devoted to the development of measures to protect astronauts from the harmful effects of ionizing radiation and microgravity. The proposed radiation shield is designed to use active and passive shielding like that of Earth's magnetosphere and ionosphere and prevent astronauts from exposure to ionizing radiation when making the journey to Mars.

MISSFIT is composed of task forces to split up the work among group members. There are currently six task forces, each dedicated to a specific aspect of the proposed conceptual design like. The coding group and magnetic field group work together to build a program that simulates particle bombardment of a spacecraft surrounded by a realistic magnetic field and two gas-filled bubbles. The goal of these task forces is to use Monte-Carlo simulation to understand how well various spacecraft designs and magnetic field configurations shield against ionizing radiation found in outer space.

Energy Loss

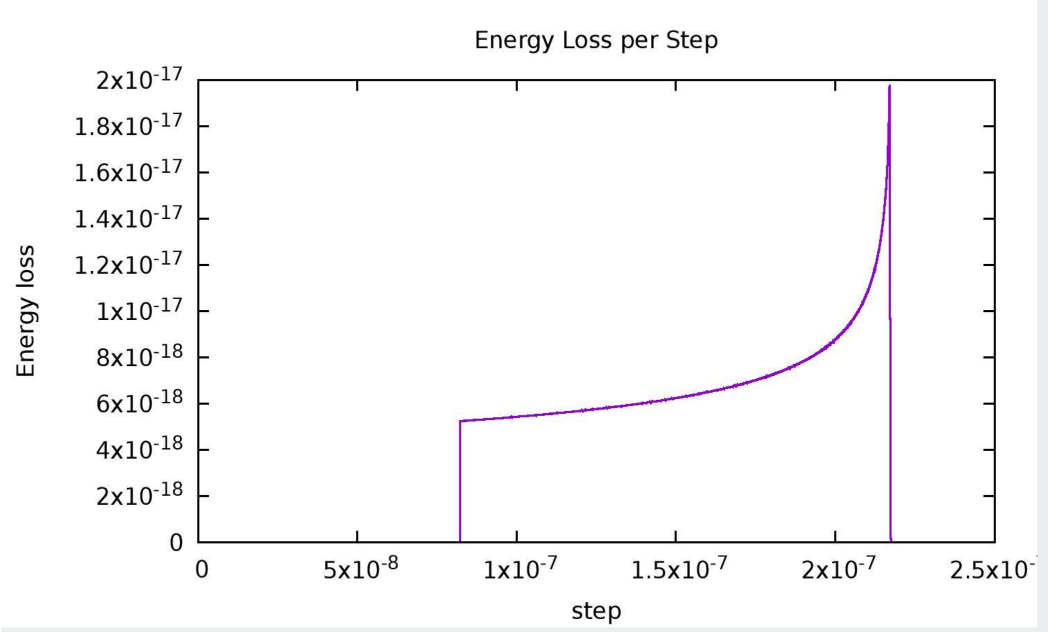


Figure 1: Energy loss per time step output from the particle propagation code of a proton traveling at 33% the speed of light through nitrogen gas. The energy loss starts when the particle enters the bubble at the end of the spacecraft and gradually increases until it reaches the Bragg peak where it deposits the majority of its energy.

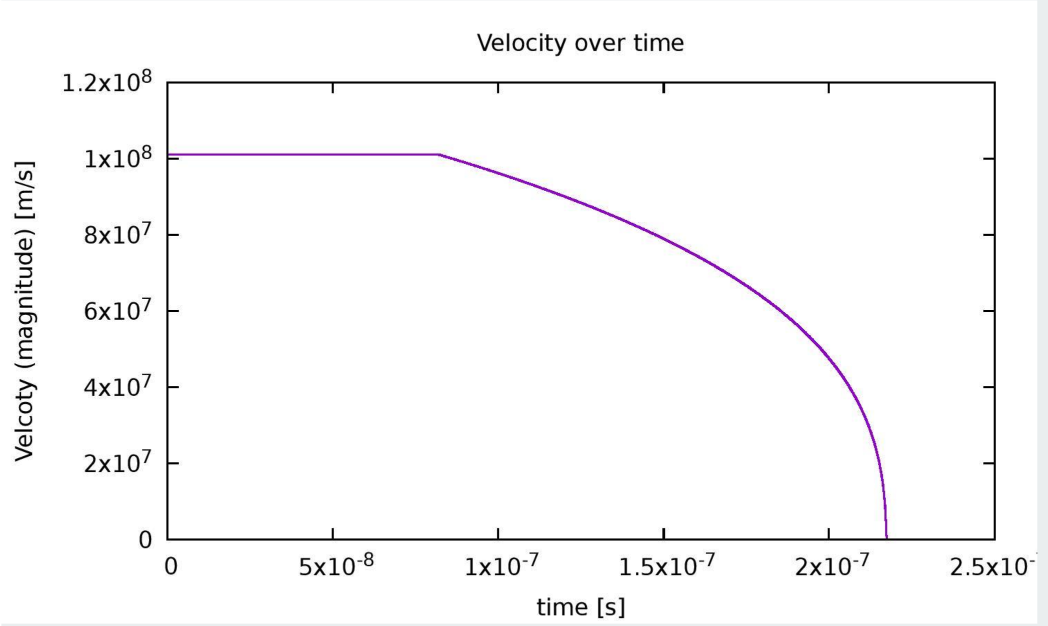
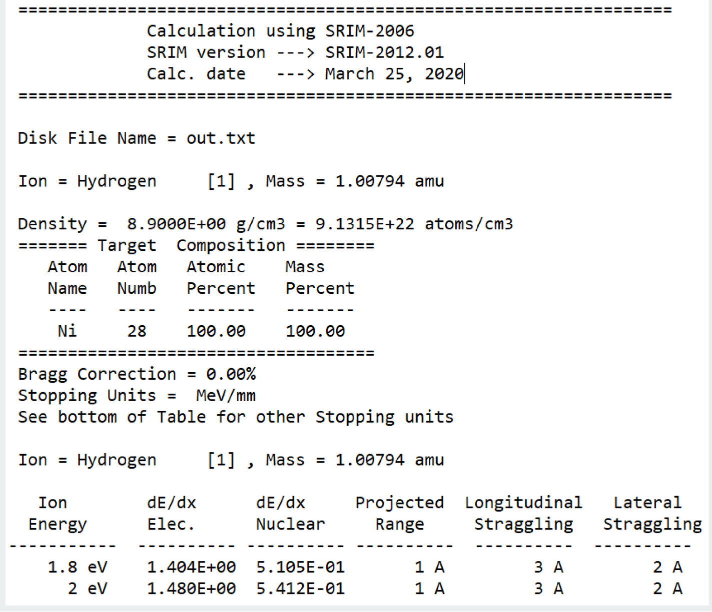


Figure 2: Velocity over time output from the particle propagation code of a proton traveling at 33% the speed of light through nitrogen gas. The velocity starts changing when the particle enters the bubble at the end of the spacecraft and gradually decrease until it comes to a stop.



```
==========================================================================
          Calculation using SRIM-2006
          SRIM version ---> SRIM-2012.01
          Calc. date   ---> March 25, 2020
==========================================================================

Disk File Name = out.txt

Ion = Hydrogen    [1] , Mass = 1.00794 amu

Density =  8.9000E+00 g/cm3 = 9.1315E+22 atoms/cm3
======= Target  Composition ========
   Atom   Atom   Atomic    Mass
   Name   Numb   Percent   Percent
   ----   ----   -------   -------
    Ni     28    100.00    100.00
====================================
Bragg Correction = 0.00%
Stopping Units =  MeV/mm
See bottom of Table for other Stopping units

Ion = Hydrogen    [1] , Mass = 1.00794 amu

  Ion        dE/dx      dE/dx     Projected  Longitudinal   Lateral
 Energy      Elec.      Nuclear     Range     Straggling   Straggling
-----------  ---------- ---------- ----------  ----------  ----------
   1.8 eV    1.404E+00  5.105E-01      1 A          3 A          2 A
     2 eV    1.480E+00  5.412E-01      1 A          3 A          2 A
```

Figure 3: Sample output from SRIM program showing nuclear and electronic stopping powers, longitudinal and lateral straggling, and projected range This output is formatted and then input to the propagation code.

Propagation Code

The particle propagation algorithm uses a second order algorithm with respect to the time step *dt*. The code takes input files for the magnetic field and energy loss.

- Uses relativistic forces to propagate the particle (Fig. 4)
- Reads the magnetic field file into memory and interpolates between grid points to obtain proper magnetic field at the particle's location (Fig. 5,6)
- Uses linear interpolation to calculate the energy loss (dE/dx) of the particle at each time step
- Energy loss is confined to spherical bubbles at either end of the spacecraft
- Sample particle trajectories shown in Fig. 7 and 8

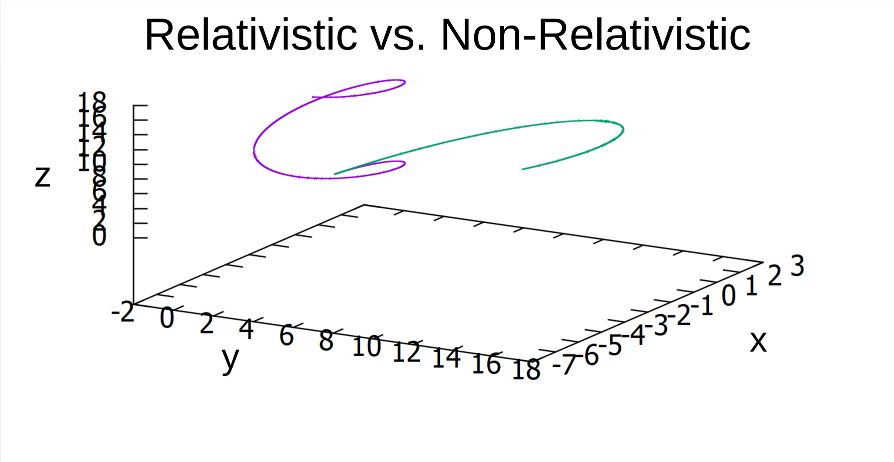


Figure 4: Non-relativistic (purple) vs. Relativistic (green) calculations for an electron moving at 0.975c in a uniform magnetic field.

Energy Loss

Energy loss of a charged particle is calculated by the Stopping and Ranges of Ions in Matter (SRIM) software [1].

- Incident particles have energies up to several GeV
- Uses Bethe-Bloch equation with corrections shown in equations 1-5 [2]
- Sample output shown in Fig. 3
- Propagation code uses this file as input to determine the stopping power at each time step (Fig. 1,2)

$$S = \frac{\kappa Z_2}{\beta^2} Z_1^2 [L_0(\beta) + Z_1 L_1(\beta) + Z_1^2 L_2(\beta)] \quad (1)$$

$$L_0 = \ln\left(\frac{2m_e c^2 \beta^2}{1-\beta^2}\right) - \beta^2 - \frac{C}{Z_2} - ln\langle I \rangle - \frac{\delta}{2} \quad (2)$$

Shell Correction   Mean Ionization Correction   Density Correction

Barkas-Anderson Correction

$$Z_1 L_1 = \frac{L_{low} L_{high}}{L_{low} + L_{high}} \quad (3)$$

$$L_{low} = 0.001E \qquad L_{high} = \left(\frac{1.5}{E^{0.4}}\right) + \frac{45000}{Z_2 E^{1.6}} \quad (4)$$

Bloch Correction

$$Z_1^2 L_2 = -y^2[1.202 - y^2(1.042 - 0.0855y^2 + 0.343y^4)] \quad (5)$$

Propagation Code

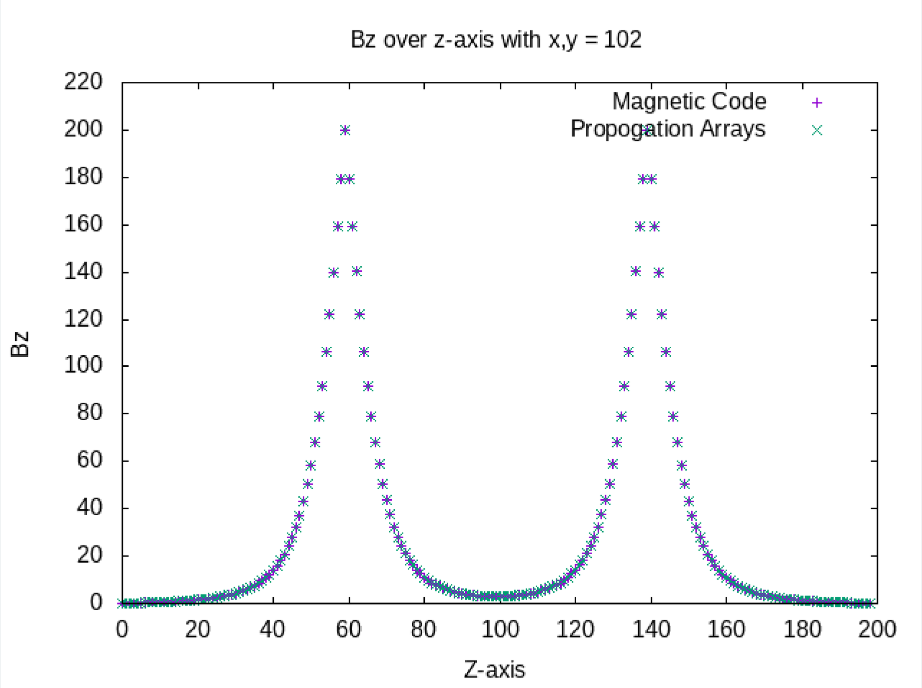


Figure 5: Magnetic field in the z-direction over the z-axis with x and y held constant at the grid point n=102.

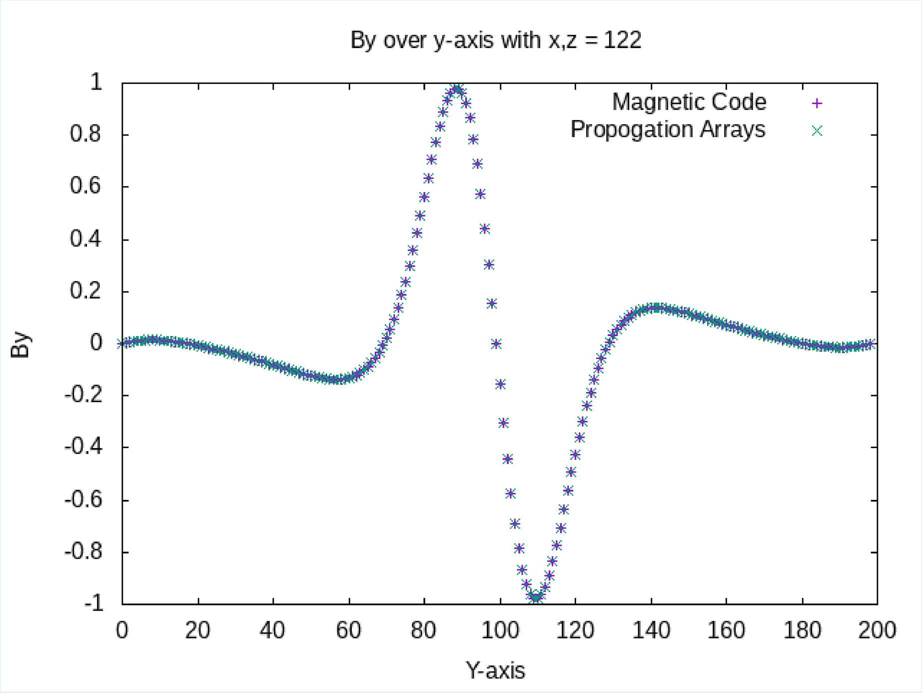


Figure 6: Magnetic field in the y-direction over the y-axis with x and z held constant at the grid point n=122.

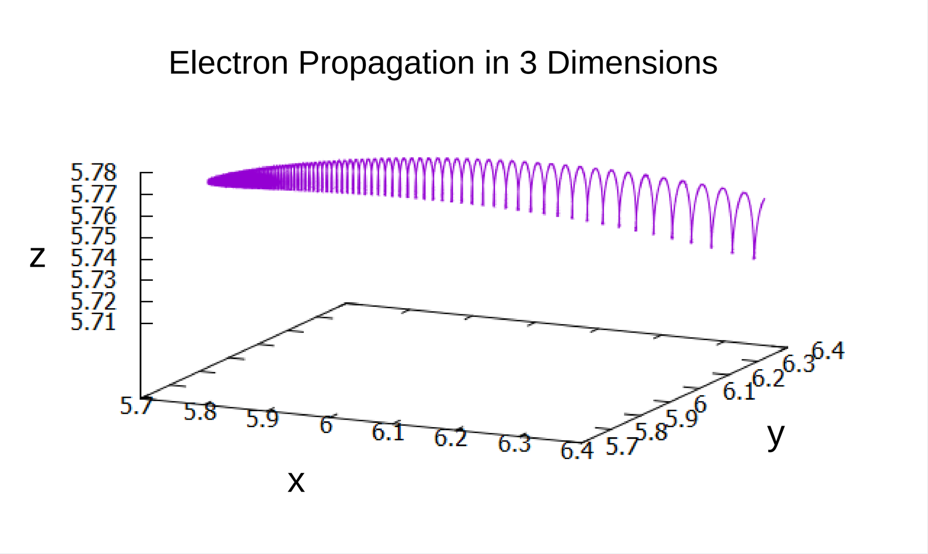


Figure 7: An electron in a magnetic field with energy loss constant over the entire region. As the particle loses energy, its spiral becomes tighter.

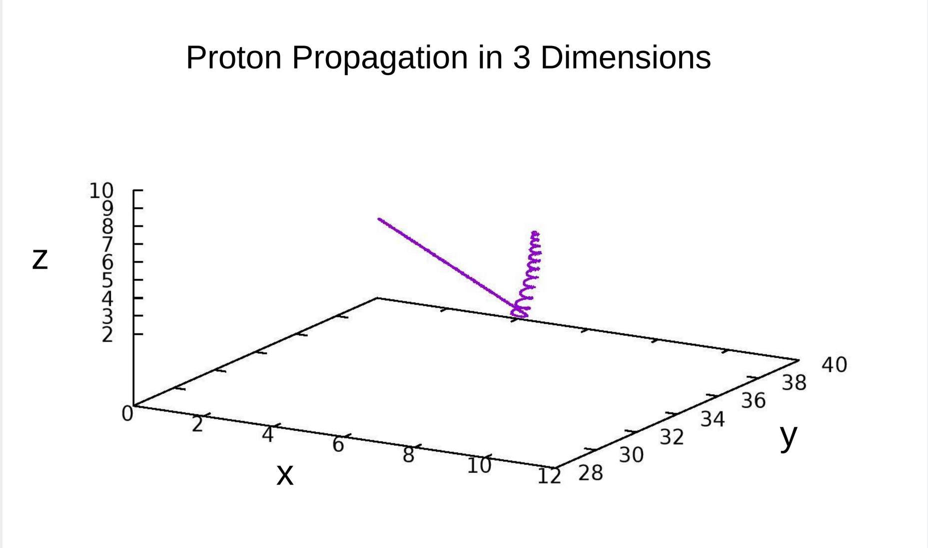


Figure 8: A proton in a magnetic field with energy loss confined to a bubble.

Active Shielding

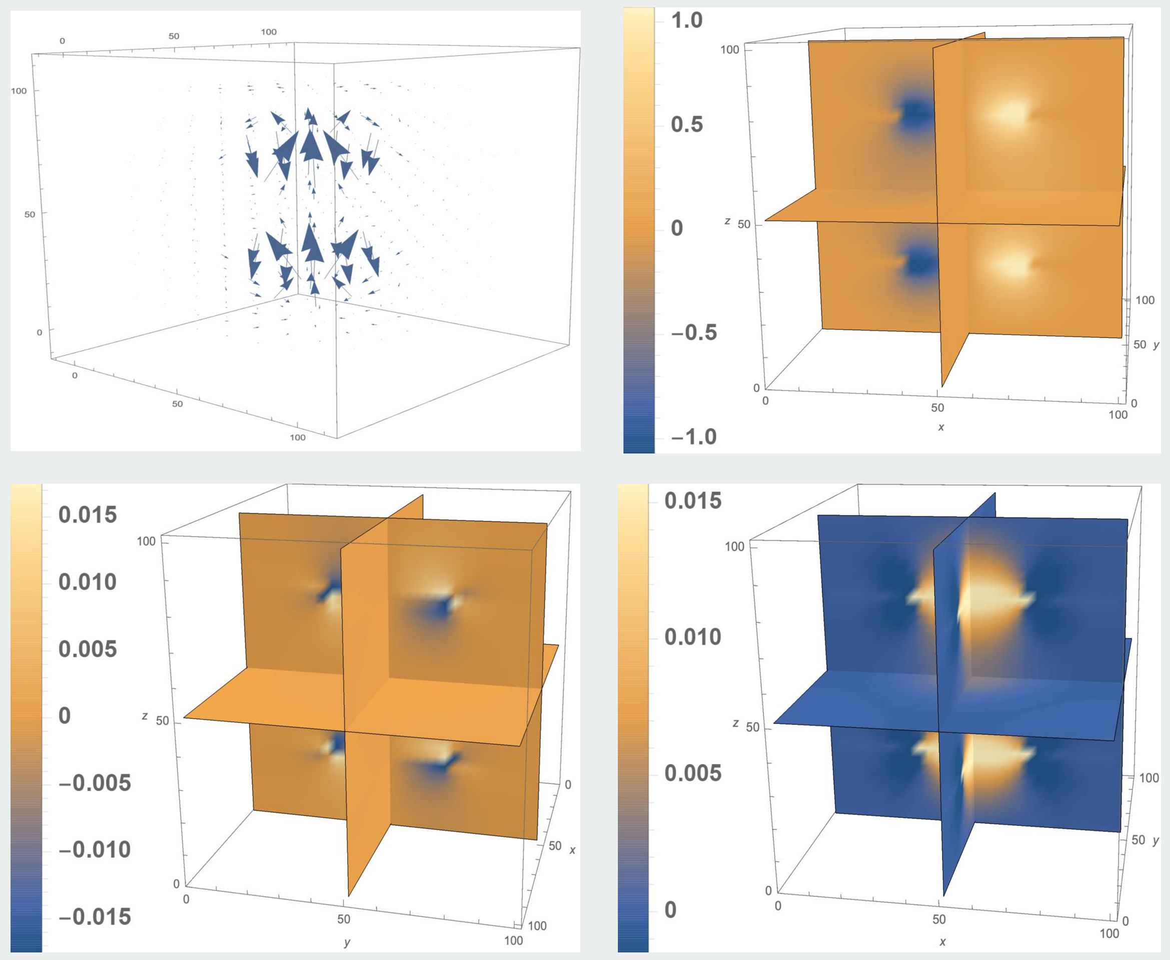
Developing the optimal system by which to deflect and capture charged particles demands exploration of magnetic fields of various forms and intensities. We developed a simulation tool that computes the value of the magnetic field at any point in space surrounding a spacecraft with variable boundary conditions.

- For static field in space: $\vec{B} = \vec{\nabla} \times \vec{A}$ and $\nabla^2 \vec{A} = 0$.
- Taylor series expansions yields numerical approximation of the Laplacian in form of the mean of the surrounding mesh points.
- Successive optimal overrelaxation algorithm with parity ordering [3]
  - Approximate value with residual, measure of deviance from arithmetic means, scaled by optimization parameter $f_{opt} = 2 - \frac{2\pi}{n}$.
  - Parity ordering: mesh points systematically assigned 0 or 1 to queue next calculations and force faster convergence.
- Partial derivatives approximated via finite difference central differentiation method,

$$\frac{\partial A_z}{\partial y} \approx \frac{A_z(i,j-1,k) - A_z(i,j+1,k)}{2dy}.$$

- The following plots are of parallel and opposing dipoles with a grid size of 40 dm:

Figure 6: The three contour plots were generated via two current loops circulating the bases of a cylinder in the **same** direction. The radii of the bases are 2.0 meters and the height of the cylinder is 5.0 meters. The top left plot is the magnetic vector field; the top right plot is of the A_y field, and the lower plots are of the B_y and B_z fields respectively. The intensity of the initial vector potential is equal to 1.0.



Acknowledgments

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References

[1] Ziegler, James F, et al. "SRIM - The Stopping and Range of Ions in Matter." SRIM, SRIM-2013, 2013, www.srim.org/.
[2] Zigler, James F. "The Stopping of Energetic Light Ions in Elemental Matter."(1999) J. Appl. Phys/Rev. Appl. Phys. 85, 1249-1272.
[3] Hansen, Per Brinch, "Numerical Solution of Laplace's Equation" (1992). Electrical Engineering and Computer Science Technical Reports. 168.