Calculation of Coronal Radio Emission in Theory and from Tecplot Simulation Data

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1 The Radio Emissivity in the Solar Corona

Theoretically and observationally [1], the major component of the plasma radio-emission in the solar corona is given by the second harmonic plasma emissivity:

$$j_{sh}(2\omega_p) = 5.83 \times 10^{-12} \left(\frac{T_e}{T_{e0}}\right)^{3/2} \frac{|E|^4}{\sqrt{n_0}}, \text{ watts m}^{-3}\,\text{sr}^{-1}, \tag{1}$$

where $\omega_p = \left(\frac{n_0 e^2}{\epsilon_0 m_e}\right)^{1/2}$ is the plasma frequency, n_0 the electron number density, T_e the electron temperature, $T_{e0} = 1.2 \times 10^5$ kelvin and $|E|$ the electric field of the Langmuir turbulence [2]. The latter can be calculated from the current density J and n_0, which can be taken from a MHD-model of the solar corona, and the electron beam number density n_b, which can be estimated from satellite observations. In particular, we have

$$|E| = \left(\frac{n_b}{n_0}\right)^{1/6} \frac{1}{e}\sqrt{\frac{2m_e}{\epsilon_0 n_b}}\, J \tag{2}$$

as a theoretical result [3], which has been verified in laboratory-experiments [4]. The measurements of the ISEE-3 satellite at Earth's orbit yielded $n_b/n_0 \approx 10^{-9} - 10^{-6}$ [5]. Since the measured velocity of the electron beams $v_b \approx 0.1 - 0.3\,c$, the propagation of the beam electrons from the solar corona to 1 AU is very quick. Thus, it is generally believed that the beam density n_b in the solar corona is roughly the same as at 1 AU.

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[1] Gurnett, D. A., R. R. Anderson, and R. L. Tokar, Plasma oscillations and the emissivity of type III radio bursts, in *Radio Physics of the Sun,* edited by M. R. Kundu and T. E. Gergely, pp. 369-379, IAU, 1980.

[2] Papadopoulos, K., M. L. Goldstein, and R. A. Smith, Stabilization of electron streams in type III solar radio bursts, *Astrophys. J., 190,* 175-185, 1974.

[3] Manheimer, W. M., Strong turbulence theory of nonlinear stabilization and harmonic generation, *Phys. Fluids, 14,* 579-+, 1974.

[4] Whelan, D. A., and R. L. Stenzel, Nonlinear energy flow in a beam-plasma system, *Phys. Rev. Lett., 50,* 1133-1136, 1983.

[5] Lin, R. P., W. K. Levedahl, W. Lotko, D. A. Gurnett, and F. L. Scarf, Evidence for nonlinear wave-wave interactions in solar type III radio bursts, *Astrophys. J., 308,* 954-965, 1986.

Dulk, 1985 [6] looked at frequency-dependent absorption-coefficients and optical depths in the solar corona. He found, that the cut-off frequency, above which the fundamental plasma-radiation is strongly reabsorbed, is roughly 10 - 30 MHz. Below this limit, the intensity of the fundamental plasma-radiation is maximally 1/16 of the intensity of the second harmonic plasma-radiation. The cut-off of the second harmonic plasma-radiation due to strong reabsorption happens at frequencies of about 2 - 5 GHz. Thus, in the frequency-range, where radio-telescopes like LOFAR are operating, the component of the fundamental plasma-emission can be neglected.

Dulk, 1985 also looked at the emissivity of the gyrosynchrotron-radiation of mildly relativistic electrons in the solar corona. He found

$$j_{cyclo}(\omega_g) = 1.294 \times 10^{-33} \frac{B}{[\mathrm{Gauss}]} \frac{n_0}{[\mathrm{m}^{-3}]}, \ \mathrm{watts\,m^{-3}\,Hz^{-1}\,sr^{-1}}, \tag{3}$$

where $\omega_g = \frac{eB}{m_e}$ is the electron-gyrofrequency, B the magnetic field, and a medium value of the pitch-angle of the electrons is inserted. This formula has been used in various studies of the solar corona, where it has been found that its general deviation from the observations is less than 20 % [7].

Since $|E| \propto (1/R)^{1.6}$, $T_e \propto (1/R)^{2/7}$, $n_0 \propto (1/R)^2$ and $B \propto (1/R)^2$, where R is the heliocentric distance, $j_{\mathrm{sh}} \propto (1/R)^6$ and $j_{\mathrm{cyclo}} \propto (1/R)^4$. So farther away from the Sun, the cyclotron-emission is dominant, whereas the plasma-emission is dominant close to the Sun, unless there are strong magnetic fields.

Bremsstrahlung is the third component of the radio-emission of the solar corona. The emissivity of the Bremsstrahlung in the solar corona grows with the square of the frequency ν^2 for low frequencies, and reaches a saturation-level for higher frequencies [8]. This spectrum of the Bremsstrahlung is usually corrected out of radio-measurements and is not needed to be modeled in a simulation-calculation.

2 Handling of the BATS-R-US CME-simulation data with Tecplot

2.1 Data-loading and plotting

One object in the solar corona that is of interest to be studied in radio emissions is a coronal mass ejection (CME). Such a transient event can be modeled within more-dimensional MHD-calculations. Three-dimensional MHD-calculations of that kind can be carried out with the Michigan BATS-R-US code. The output-data of that code can

[6] Dulk, G. A., Radio emission from the sund and stars, *Ann. Rev. Astron. Astrophys., 23,* 169-224, 1985.

[7] Aschwanden, M., *Physics of the Solar Corona,* Springer, New York, 2004.

[8] Aschwanden, M., *Physics of the Solar Corona,* Springer, New York, 2004.

be handeled with the visualisation-software Tecplot. Tecplot can be used to calculate the radio-emission according to the emission-model above, and to compute synthetic radio-maps of a CME-eruption. The latter can be compared with real measurements like LOFAR radio-observations. Here, we describe how the BATS-R-US output-data can be handeled.

On SISCOE, Tecplot can be called with

```
tcsh% tecplot &
```

When the Tecplot-window has opened, goto

File ⇒ Open Data File

A Dialog-Box opens, where you can double-click on one directory-name in the left window in order to open it, and double-click on the entry that ends with two dots in order to navigate one level higher in the directory-tree. In the right window, you can select a wanted file in an opened directory.

Navigate to the directory "/usr/people/pgi/3D_Manchester/". This is where the simulation data of a CME-simulation have been stored that has been carried out by Chip Manchester. You will find the following entries for "*.plt" binary simulation-data files:

new3d_mhd_3_n084813.plt
new3d_mhd_3_n085274.plt
new3d_mhd_3_n085804.plt
new3d_mhd_3_n086428.plt
new3d_mhd_3_n087076.plt
new3d_mhd_3_n087704.plt
new3d_mhd_3_n088316.plt
new3d_mhd_3_n088915.plt
new3d_mhd_3_n089502.plt
new3d_mhd_3_n090072.plt
new3d_mhd_3_n090630.plt
new3d_mhd_3_n091175.plt
new3d_mhd_3_n091710.plt
new3d_mhd_3_n092236.plt
new3d_mhd_3_n092751.plt
new3d_mhd_3_n093254.plt
new3d_mhd_3_n093745.plt
new3d_mhd_3_n094224.plt
new3d_mhd_3_n094693.plt
new3d_mhd_3_n095156.plt
new3d_mhd_3_n095613.plt
new3d_mhd_3_n096064.plt
new3d_mhd_3_n096509.plt

new3d_mhd_3_n096947.plt
new3d_mhd_3_n097380.plt
new3d_mhd_3_n097807.plt
new3d_mhd_3_n098228.plt
new3d_mhd_3_n098644.plt
new3d_mhd_3_n099055.plt
new3d_mhd_3_n099460.plt

Each file contains a temporal cut for a specific time through the simulation-data of the run for a CME that propagates from 1 $R_{\odot}$ to 32 $R_{\odot}$, where $R_{\odot}$ is one solar radius.

Select the file "new3d_mhd_3_n093254.plt", which is our standard-file, where the CME has reached about 6 $R_{\odot}$ and has evolved significantly. Press "OK" in the file-opening dialog-box. The data will be loaded.

Deselect "Mesh", "Lighting" and "Translucency" in the column that defines the Zone Layers options.

In the same column, select "Contour" and press the botton with the three dots next to that field for the option "3D Cartesian" of the Plot Types.

A "Contour Details" dialog-box will appear. In the field "Var" you can scroll through a list of variables that can be displayed. That list contains the following variables:

V1: X R
V2: Y R
V3: Z R
V4: ‘r g/cm3
V5: U_x km/s
V6: U_y km/s
V7: U_z km/s
V8: B_x Gauss
V9: B_y Gauss
v10: B_z Gauss
v11: p dyne/cm2
v12: J_x uA/m2
V13: J_y uA/m2
v14: J_z uA/m2

V1 - V3 are the cartesian coordinates in solar radii. V4 is the density in gramms per cube-centimeter, V5 - V7 are the components of the velocity in kilometer per second, V8 - V10 are the components of the magnetic field in Gauss, V11 is the pressure in dyne per square-centimeter, and V12 - V14 are the components of the current density in mycro-ampere per square-meter.

You could select V4 in order to produce a sample contour-plot for the density.

In the "Contour Details" dialog-box you can select the "More"-button in order to open the extended "Contour Details" dialog-box. In the token "Levels" you will find a list of the values of the levels that the contour plot will draw as separation-lines of neighboring colors. If you select "New Levels", a "Enter Contour Level Range" dialog-box will appear, where you can define your own “Minimum Level”, “Maximum Level” and “Number of Levels” in order to refine the display of your plot. Furthermore, you can switch to an “Exponential Distribution” of the contour-levels by selecting the corresponding button. You can end your choice by pressing “OK”.

If you open the “Legend”-token, you can define a legend for your plot. Select “Show Contour Legend” and “Legend Box: Filled” in order to create a labeled legend on a filled background in your plot. If you have chosen to many contour-lines, the legend will not fit on your plot. Then, aditionally select “Reseize Automatically”.

Press “Close” in order to finish your Levels- and Legend-definitions.

When you have chosen your output-variable, the corresponding data will automatically be loaded on the display of the 3D cartesian plot.

In the main menue-line you can select “Data”, “Extract”, and then “Slices from plane”. There, you can define “Constant Z = 0” in order to define the plane Z = 0 as the plane of your contour-plot. Then, press “Extract”. You can define a second contour-plot in the same plot-frame by defining “Constant X = 0” and then pressing “Extract”.

Note, that you won’t see the two contour-plots immediately. In order to display them, activate “Zone Style” in the main window. A “Zone Style” dialog-box will appear. In the main window, the three zones that you have created are listed. Select the first entry “PostGrid” and press the “Zone Show”-button. A drag-down menue will appear, where you can “deactivate” the display of the postgrid zone. After that, your double contour-plot will appear in the display. It will look like in Figure 1.

If you want to save your plot, you need to select “File” and “Export”. In the dialog-box that opens, select “Postscript-File” and “Colour”. Then choose the path-name and the name of your plot-file and press “OK”.

2.2 Calculating new quantities from simulation-data

If you want to calculate new quantities from your simulation-data, you need to define equations in Tecplot that act on the variables that are there already.

Select “Data” in the main menue and “Alter”. Then choose “Specify Equations”. A “Specify Equations” dialog-box will appear. In the “Equations”-window you can enter your equations. For example, the sequence

```
{J} = sqrt(v12**2 + v13**2 + v14**2) * 1.0e-6
{n0} = 5.978715772e29 * V4
{p_si} = V11 * 1.0e-1
{T} = {p_si} / (1.3806e-23 * {n0})
{nb} = 1.0e-9 * {n0}
{E2} = 1.0e0 / 9.0e0 * ({nb} / ({n0} + 1.0e-31))**(-0.666666666e0)
       * 7.214134962e19 * {J}**2 / ({n0} + 1.0e-31)
{j_sh watts/(m^3 sr)} = 5.83e-12 * sqrt({T} / 1.2e5)**3
       * {E2}**2 / sqrt({n0} + 1.0e-31)
```

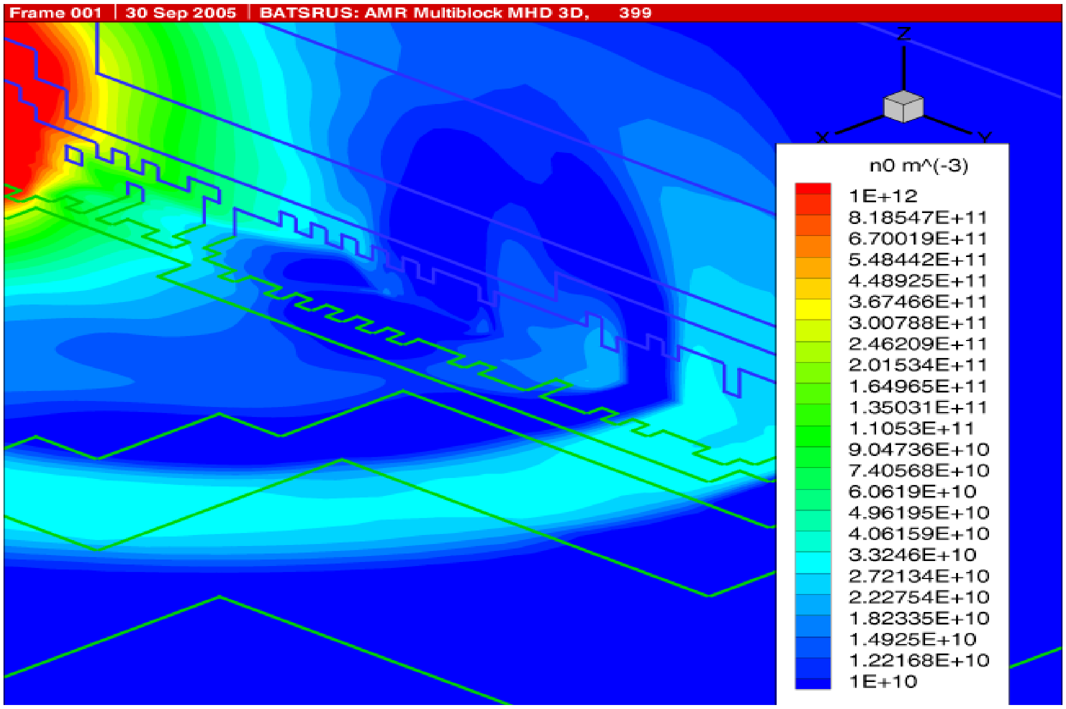

Figure 1: Contour plots of the density

```
{B} = sqrt(v8**2 + v9**2 + v10**2)
{j_cyclo watts/(m^3 Hz sr)} = 1.293887135e-26 * {B} * 1.0e-6 * {n0} * 1.0e-1
{T / T0} = {T} / 1.2e5
{n0 m^(-3)} = {n0}
{J A/m^2} = {J}
{B gauss} = {B}
{T kelvin} = {T}
{E volt m^(-1)} = sqrt({E2})
{result array} = 0.0e0
```

defines the emission-model of the first chapter. The conversion-factors that are inserted are due to physical natural constants and unit conversion-factors. A constant 1.0e-31 is added, where a quantity in the denominator can become smaller than machine-accuracy. We note that variable V21 is the emissivity $j_{\rm sh}$ of the plasma-radiation and V23 is the emissivity $j_{\rm cyclo}$ of the synchrotron-radiation. V30 is a result array for later internal calculations that has been set to zero initially.

Now press “Compute” in order to generate the new variable arrays. Press the button with the three dots next to the “Contour”-field in the main window in order to open the “Contour Details” dialog-box again. In the “Var”-field you will find all new variables that can be selected for plotting-issues.

Remark: In the “Specify Equations” dialog-box you can press the button “Save Equations”. Then store the equations, e.g., in “/usr/people/pgi/3D_Manchester/j_sh.eqn”.

When you enter Tecplot in the next session, you can go to the “Specify Equations” dialog-box, press “Load Equations” and load the equations from the file “/usr/people/pgi/3D_-Manchester/j_sh.eqn”, where you have stored them in the previous session. Press “Compute” in order to calculate the new variables. With this procedure you will not have to input your equations over and over again.

The figures 2, 3, 4 and 5 display the current density J, the electric field of the Langmuir-turbulence E, the temperature T and the emissivity $j_{\rm sh}$ of the plasma-radiation.

One can see a red “eye” in about the middle of the plot of the current density that denotes the reconnection-region at the rear of the CME, where the magnetic field that anchors the magnetic cloud of the CME with the solar surface is dissolved. From that region reconnection-jets are directed towards the Sun. There is a current-system at the front of the CME, where the reverse shock of the shock that is driven by the CME hits the body of the CME. The forward-shock drives another current-system that propagates ahead of the CME.

The electric field of the Langmuir-turbulence displays a similar picture. Yet, there is a distinct fine-structure within the reconnection-region for that field.

The temperature displays the expected large heating of the reconnection-region, where magnetic field energy is dissipated. The core of the CME has a much smaller temperature.

The plasma-emissivity is in fact a combination of the pictures of the electric field of the Langmuir-turbulence and the temperature. The plasma-emissivity shows similar features in the reconnection-region as the electric field of the Langmuir-turbulence. Yet, the front-boundaries of that reconnection-region are not so wide-spread in the plasma-emissivity plot, and shaped as in the temperature-picture. The body of the CME shows a decreased plasma-emissivity as the temperature of the CME is decreased in the core of the CME.

2.3 Interpolating data-sets

The data of the BATS-R-US code have a block-oriented structure, i.e. they are not given on an equally spaced cartesian grid. This is the reason why it is not possible to define array-manipulations with single array-elements in an easy manner. In order to compute, e.g., convolution-products of the arrays that will produce two-dimensional radio maps, one needs to interpolate the data-sets to a cartesian grid first.

This is done in the following way. Select “Data” in the main window and then “Create Zone” and “Rectangular...”. A dialog-box will open, where you can define the dimensions. E.g., choose I = 128, J = 128 and K = 128 in the dimension definition fields for a grid with 128 x 128 x 128 grid-points. Ensure that the coordinates range from XMin = -32 to XMax = 32, YMin = -32 to YMax = 32 and ZMin = -32 to ZMax = 32. Then press the “Create”-button.

Next, open “Data” again and choose “Interpolate”. There is a choice between “Linear”-, “Inverse-Distance”- and “Kriging”-Interpolation in a pull-down menue. If sufficient, choose “Linear” Interpolation. The other interpolations are pretty slow. A dialog-box will open, where the possible “Source Zone(s)” are listed to the left. You will see entries

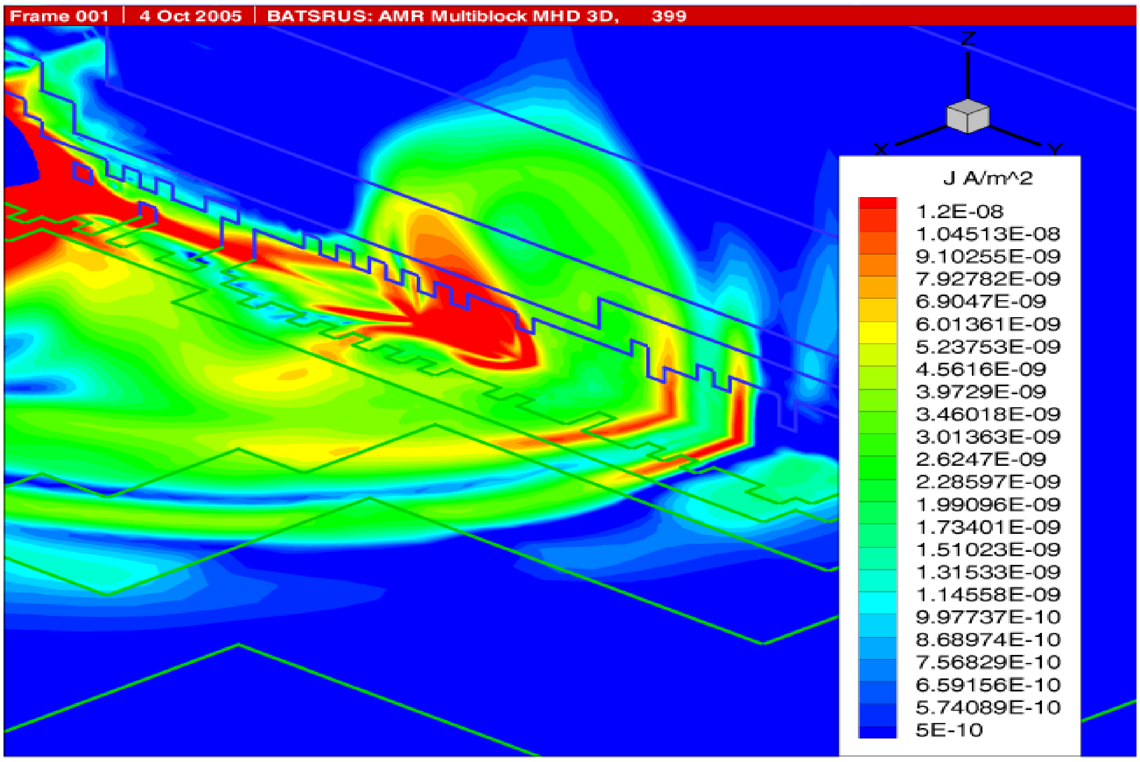

Figure 2: Contour plots of the current density

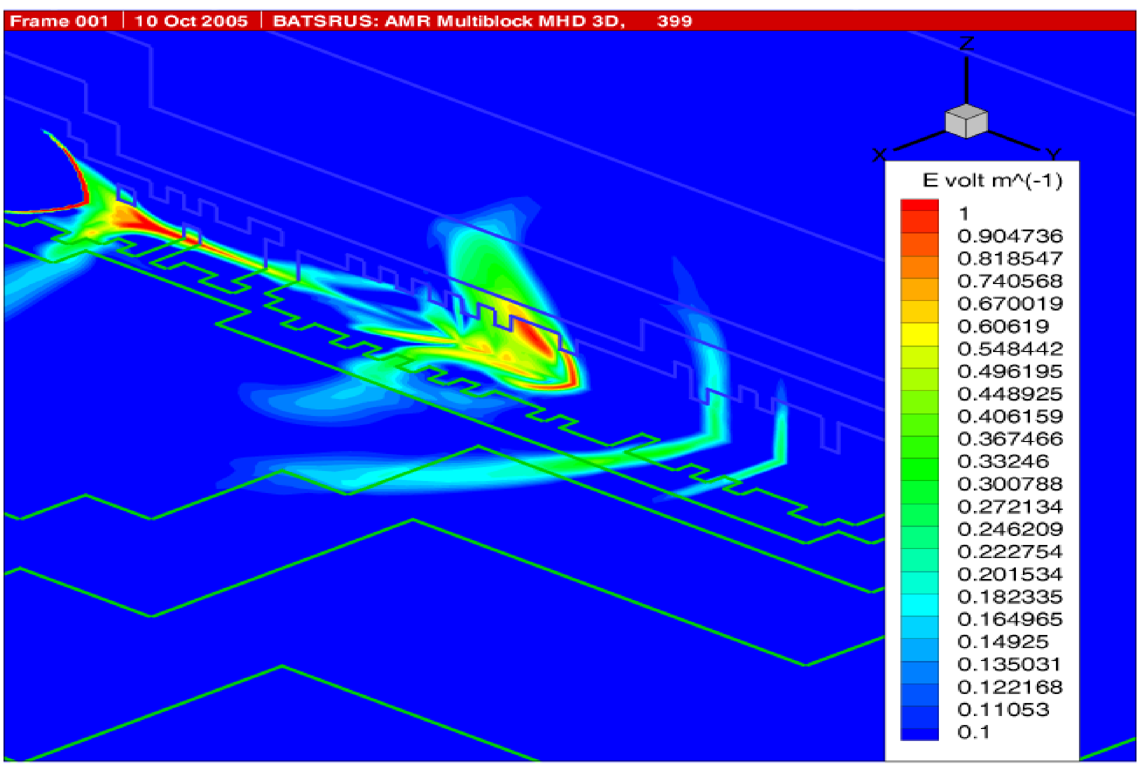

Figure 3: Contour plots of the electric field of the Langmuir-turbulence

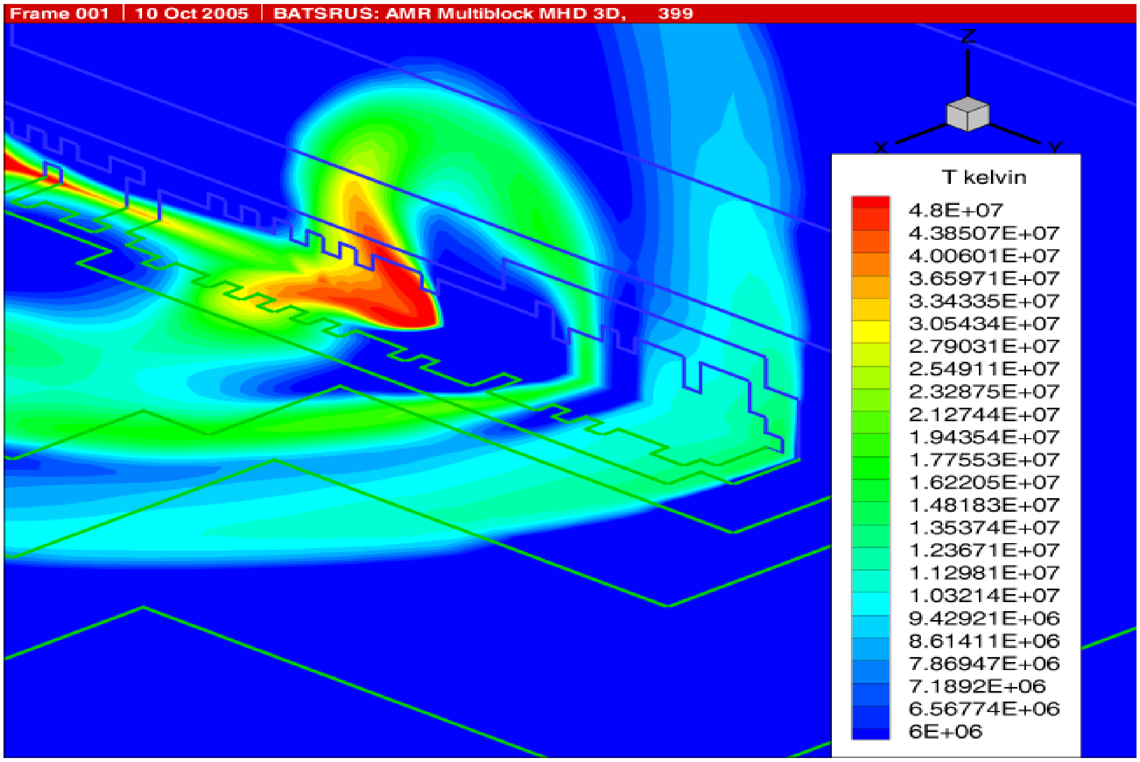

Figure 4: Contour plots of the Temperature

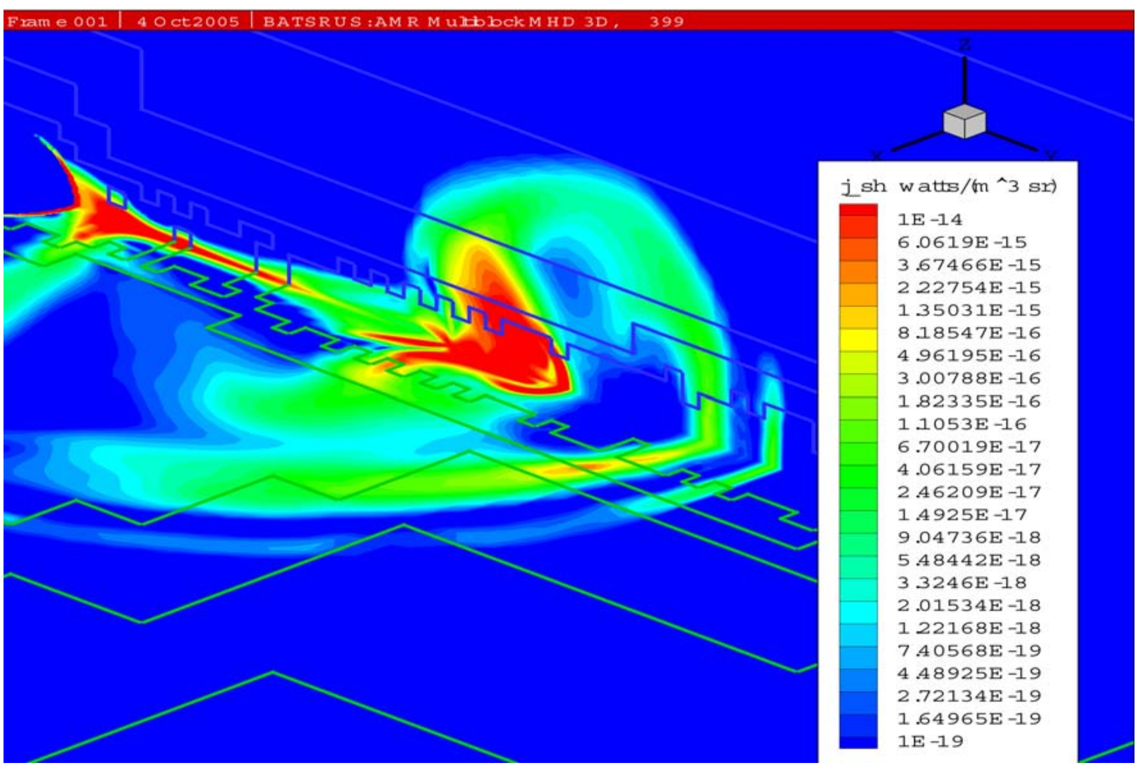

Figure 5: Contour plots of the second harmonic plasma-emissivity

“1: PostGrid” and “2: Rectangular” in the list. Choose “1: PostGrid”. To the right a column with the “Variables” is listed, where you can select the variables that should be interpolated. Choose all variables.

Below these entries, a list with the possible “Destination Zone” is shown. Again, there are the entries “1: PostGrid” and “2: Rectangular Zone”. Select “Rectangular Zone”. Let the option “Outside Points” set to “Constant”. Press “Compute”. Tecplot will interpolate the data from the PostGrid to the rectangular grid.

2.4 Writing data-sets

You will need to save the newly computed data-sets and the interpolated data-sets as well. Select “File” in the main window and “Write Data File”. A “Write Data File Options” dialog-box will appear. Select “Field Data”, “Binary” and “Block”. Chose “1: PostGrid” for the zone and let all variables be selected. Select “Associate Layout with Newly Saved Data File” and press “OK”. A dialog-box will open, where you can select the path-name of the output-file. E.g., define “/usr/people/pgi/3D_Manchester/j_sh_mhd_3_n093254.plt”. Press “OK” again. The data of the PostGrid will be stored in the file specified.

In order to store the rectangular zone data, you can select “File”, “Write Data File”, “Field data”, “Binary”, “Point”, “2: Rectangular zone”, let all variables be selected, “Associate Layout with Newly Saved Data File”, “OK”, “/usr/people/pgi/3D_Manchester/rectangular_binary.plt” and “OK”.

2.5 Using macros

You can use macros in order to make processes in Tecplot automatic. We will need such macros for the calculation of discretized convolution-integrals of the emissivity-data on the rectangular grid that yield two-dimensional radio maps. A macro is a file with the extension “*.mcr” that starts with the command-line “#!MC 1000” and contains a sequence of Tecplot-commands. You can edit such a macro-file with your Unix file-editor, e.g. with “vi” or “emacs”. In the following you will find an example macro “try_III.mcr” that I have commented. In a working macro-program the comments need not be included, however.

```
#!MC 1000

$!READDATASET "/usr/people/pgi/3D_Manchester/rectangular_binary.plt"

comment: The created rectangular data set is read into zone 1.

$!VARSET |value| = 0.0

comment: The variable ‘‘|value|’’ is set to zero.
```

```
$!VARSET |inew| = 5

comment: The loop-counter |inew| for the i-loop is set to its
         initial value.

$!LOOP 9

comment: The i-loop starts and has 9 repetitions.

$!VARSET |inew| = (|inew|+13)

comment: The i-loop counter is increased by 13.

$!VARSET |jnew| = 5

comment: The j-loop counter is set to its initial value.

$!LOOP 9

comment: The j-loop starts.

$!VARSET |jnew| = (|jnew|+13)

comment: The j-loop counter has its increment.

$!VARSET |knew| = 5

comment: The k-loop counter is set to its initial value.

$!LOOP 9

comment: The k-loop starts.

$!VARSET |knew| = (|knew|+13)

comment: The k-loop counter has its increment.

$!VARSET |indx| = (128*128*(|knew|-1)+128*(|jnew|-1)+|inew|)

comment: This is the way the floating-index of an array-element with
         the indices i=|inew|, j=|jnew|, k=|knew| is defined in Tecplot.

$!VARSET |inew1| = (|inew|)
$!GETFIELDVALUE |x|
  ZONE = 1
```

```
  VAR  = 1
  INDEX = |inew1|

comment: The x-coordinate is read in.

$!VARSET |jnew1| = (128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |y|
  ZONE = 1
  VAR  = 2
  INDEX = |jnew1|

comment: The y-coordinate is read in.

$!VARSET |knew1| = (128*128*(|knew|-1)+128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |z|
  ZONE = 1
  VAR  = 3
  INDEX = |knew1|

comment: The z-coordinate is read in.

$!VARSET |inew1| = (|inew|-13)
$!GETFIELDVALUE |x1|
  ZONE = 1
  VAR  = 1
  INDEX = |inew1|

comment: The x-coordinate with one increment subracted is read in.

$!VARSET |jnew1| = (128*(|jnew|-13-1)+|inew|)
$!GETFIELDVALUE |y1|
  ZONE = 1
  VAR  = 2
  INDEX = |jnew1|

comment: The y-coordinate with one increment subracted is read in.

$!VARSET |knew1| = (128*128*(|knew|-13-1)+128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |z1|
  ZONE = 1
  VAR  = 3
  INDEX = |knew1|

comment: The z-coordinate with one increment subracted is read in.
```

```
$!GETFIELDVALUE |j_sh|
  ZONE = 1
  VAR  = 21
  INDEX = |indx|

comment: The value for the second harmonic emissivity is read in.

$!VARSET |value| = (|j_sh|*(|x|-|x1|)*(|y|-|y1|)*(|z|-|z1|)/
                    (|x|**2+|y|**2+|z|**2))

comment: The emissivity is multiplied with the cell-volume
         (|x|-|x1|)*(|y|-|y1|)*(|z|-|z1|). This yields the
         power that is radiated into a spatial angle of one
         steradiant. The multiplication with
         1/(|x|**2+|y|**2+|z|**2)
         yields the power that flows through a surface of one square-meter
         at a distance of sqrt(|x|**2+|y|**2+|z|**2).

$!SETFIELDVALUE
  ZONE = 1
  VAR  = 30
  INDEX = |indx|
  FIELDVALUE = |value|

comment: The result is stored in the variable V30, which is the
         ``result array'', at the grid point that corresponds to
         the floating-point index |indx|.

$!ENDLOOP

comment: End of the k-loop.

$!ENDLOOP

comment: End of the j-loop.

$!ENDLOOP

comment: End of the i-loop.

$!WRITEDATASET "/usr/people/pgi/3D_Manchester/rectangular_binary_III.plt"

comment: The data-set with the modified data is stored in the file
         /usr/people/pgi/3D_Manchester/rectangular_binary_III.plt.
```

In order to run your macro, go to “File” in the main Tecplot-window. Select “Macro” and then “Play”. In the Load/Play Macro File dialog box that appears, you can specify your macro file name, e.g. “/usr/people/pgi/3D_Manchester/try_III.mcr”, when this is the place where your macro is stored. Click “OK”. Tecplot immediately will start playing the specified macro file.

Go to “File” and “Macro” again. Use the “View”-option in the pull-down menue. A “Macro Viewer” dialog-box will appear. In the window to the top a label “>” will indicate which Tecplot-command is currently executed. You can press “Reset” in order to go to the first command in the macro. Press “Go” and the macro will start from the beginning. Alternatively, you can press “Step” in order to process your macro step by step from command to command. Use the “Watch Variables”-button in order to view the content of specified variables for debugging-purposes. A “Macro Variables” dialog-box appears, where you can input variable names in the fields beneath the caption “User-Defined or Internal Variable”. E.g., you can input “value” or “j_sh” in order to watch the current assigned values in the “Value”-column.

Remark: Note that in interactive mode macros are not running very fast. It is faster to run macros in batch mode. For that you need to give the command

```
tcsh% tecplot -b try_III.mcr
```

from the Unix command line.

2.6 Calculation of the convolution integral

We specify a coordinate in a two-dimensional plane, where a radio-telescope measures a signal. The measured signal at that coordinate is the superposition of all differential signals that stem from different volume-elements of a radio-source. If one of these volume-elements has a specific radio-emissivity, the power that it radiates is given by its emissivity times the volume-element. The energy-flow through one square-meter of the receiving plane at the coordinate specified is given by this product times the inverse square of the distance between the volume-element and the specified point in the two-dimensional plane. For the integrated signal at the point specified, all such contributions of all volume-elements of the radio-source have to be summed up.

The following macro-program “try_XVI.mcr” calculates the convolution-sum that is described above at 128 x 128 points in a plane at Earth’s orbit that is perpendicular to the x-axis, where the simulation-box with the CME-eruption at about 6 $R_\odot$ is divided into 216 radiating cells.

```
#!MC 1000

$!READDATASET "/usr/people/pgi/3D_Manchester/rectangular_binary.plt"

$!VARSET |knewout| = 0
$!LOOP 128
```

```
$!VARSET |knewout| = (|knewout|+1)

$!VARSET |jnewout| = 0
$!LOOP 128
$!VARSET |jnewout| = (|jnewout|+1)

$!VARSET |inewout| = 32

$!VARSET |x2| = 215.5172414e0

$!VARSET |jnewoutindex| = (128*(|jnewout|-1)+|inewout|)
$!GETFIELDVALUE |y2|
  ZONE = 1
  VAR  = 2
  INDEX = |jnewoutindex|

$!VARSET |knewoutindex| = (128*128*(|knewout|-1)+128*(|jnewout|-1)+|inewout|)
$!GETFIELDVALUE |z2|
  ZONE = 1
  VAR  = 3
  INDEX = |knewoutindex|

$!VARSET |value| = 0.0e0
$!VARSET |frequencymean| = 0.0e0

$!RUNMACROFUNCTION "3D_LOOP" (|x2|,|y2|,|z2|)

$!VARSET |value| = (|value| * 1.0e20)
$!VARSET |frequencymean| = (|frequencymean|/(6*6*6))

$!VARSET |indxout1| = (128*128*(|knewout|-1)+128*(|jnewout|-1)+|inewout|)

$!VARSET |indxout2| = (128*128*(|knewout|-1)+128*(|jnewout|-1)+|inewout|+32)

$!SETFIELDVALUE
  ZONE = 1
  VAR  = 30
  INDEX = |indxout1|
  FIELDVALUE = |value|

$!SETFIELDVALUE
  ZONE = 1
  VAR  = 30
  INDEX = |indxout2|
  FIELDVALUE = |frequencymean|
```

```
$!ENDLOOP
$!ENDLOOP

$!WRITEDATASET "/usr/people/pgi/3D_Manchester/rectangular_binary_IV.plt"

$!QUIT

$!MACROFUNCTION
  NAME = "3D_LOOP"

$!VARSET |knew| = 1
$!LOOP 6
$!VARSET |knew| = (|knew|+21)
$!VARSET |jnew| = 1
$!LOOP 6
$!VARSET |jnew| = (|jnew|+21)
$!VARSET |inew| = 1
$!LOOP 6
$!VARSET |inew| = (|inew|+21)

$!VARSET |inewindex| = (|inew|)
$!GETFIELDVALUE |x|
  ZONE = 1
  VAR  = 1
  INDEX = |inewindex|

$!VARSET |inewindex| = (|inewindex|-21)
$!GETFIELDVALUE |x1|
  ZONE = 1
  VAR  = 1
  INDEX = |inewindex|

$!VARSET |jnewindex| = (128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |y|
  ZONE = 1
  VAR  = 2
  INDEX = |jnewindex|

$!VARSET |jnewindex| = (128*(|jnew|-21-1)+|inew|)
$!GETFIELDVALUE |y1|
  ZONE = 1
  VAR  = 2
  INDEX = |jnewindex|
```

```
$!VARSET |knewindex| = (128*128*(|knew|-1)+128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |z|
  ZONE = 1
  VAR  = 3
  INDEX = |knewindex|

$!VARSET |knewindex| = (128*128*(|knew|-21-1)+128*(|jnew|-1)+|inew|)
$!GETFIELDVALUE |z1|
  ZONE = 1
  VAR  = 3
  INDEX = |knewindex|

$!VARSET |indx| = (128*128*(|knew|-1)+128*(|jnew|-1)+|inew|)

$!GETFIELDVALUE |j_sh|
  ZONE = 1
  VAR  = 21
  INDEX = |indx|

$!GETFIELDVALUE |rho|
  ZONE = 1
  VAR  = 4
  INDEX = |indx|

$!VARSET |value| = (|value|+(|j_sh|*abs(|x|-|x1|)*abs(|y|-|y1|)*abs(|z|-|z1|)/
        ((|x|-|1|)*(|x|-|1|)+(|y|-|2|)*(|y|-|2|)+(|z|-|3|)*(|z|-|3|))*6.96e8))

$!VARSET |frequency| = (1.388509561e16*sqrt(|rho|))

$!VARSET |frequencymean| = (|frequencymean| + |frequency|)

$!ENDLOOP
$!ENDLOOP
$!ENDLOOP

$!ENDMACROFUNCTION
```

Note that “try_XVI.mcr” uses the interpolated data that have been stored in “rectangular_binary.plt”. It uses a macro-function that is called with “$!RUNMACROFUNCTION “function name” (parameter list). The function name is “3D_LOOP”. In the parameter list the values $|x2|$, $|y2|$ and $|z2|$ are assigned to the macro-function. Within the macro-function these parameters are called with $|1|$, $|2|$ and $|3|$. The convolution-sum is calculated with and stored within the variable $|value|$. $|value|$ has SI-units. Note also that for each radiating cell the frequency $|frequency|$ is calculated according to two times the plasma-frequency formula, which is proportional to the square root of the density $|rho|$. These frequencies are calculated in Hz. Since $|rho|$ does not vary much within the CME-eruption (compare with figure 1), all cells radiate with almost the same frequency. The mean frequency $|frequencymean|$ is calculated for simplicity, which is the center frequency of a very localized frequency-distribution of the measured radio-signal. The calculated convolution sums are stored at i-position 32 in the three-dimensional array V30, which is the { result array }. The frequency mean is stored uniformly at i-position 64 in the same array. Since all neigboring values in { result array } have the value zero, each convolution sum is multiplied with a factor 10^{20} in order to enhance the radio map with respect to the zero background clearly. Otherwise Tecplot would simply interpolate the complete radio map to zero, if you try to display it within a 3D cartisian plot.

In batch mode the macro program "try_XVI.mcr" uses about one hour.

The modified output data are stored in "/usr/people/pgi/3D_Manchester/rectangular_binary_IV.plt".

Start a Tecplot session. Load the "/usr/people/pgi/3D_Manchester/rectangular_binary_IV.plt" data file for a 3D cartesian plot. Select the "Contour Plot" option as it was described in the beginning of this tutorial. In the "Contour Details" dialog box choose { result array } as the display variable "Var".

Go to "Data", "Extract" and "Slices from plane". In the dialog box that appears, activate "Constant X" for the "Position" and enter "X = -16.4". This corresponds to the plane at the position i = 32 in the { result array }. Press "Extract".

Go to "Zone Style" and deactivate the "Zone Show" button for the "1: Rectangular Zone". The calculated radio map should appear.

Go to "View" and "Rotate...". You can rotate the map around the z-axis with the corresponding buttons < and > and around the y-axis in a similar manner, until you have a front view of the map. Use the "View", "Translate" option, if you want to translate your plot.

Go to the "Contour Details", "More" option and select the "Levels" token. Specify "Minimum Level: 670601408", "Maximum Level: 711202496", "Number of Levels: 400" and activate "Exponential Distribution". You can obtain the values for "Minimum Level" and "Maximum Level" from "Data" and "Data Set Info" that displays the minimum and maximum values in { result array }.

You shall see a plot like figure 6. The figure is not centered since the CME has moved about 6 - 10 $R_\odot$ along the y-axis, if its complete extend is taken into account. The point with maximum intensity corresponds to the position of the CME with the highest emissivity, which is the reconnection area. The radio intensity decreases towards the borders of the radio map, which is partly a projection effect. This decrease would be uniform, if the radio source would be a point source. Yet, the image shows a halo-structure, i.e. there is a relatively bright core with a steep decrease in intensity at its boundaries, which roughly corresponds to the region that is colour coded in yellow. That structure corresponds to a CME radio-source with a bright center, which is surrounded by spheres that belongs to shocks and that have an increased luminosity. Note that radio images like the Nançay image of a CME show such a halo structure.

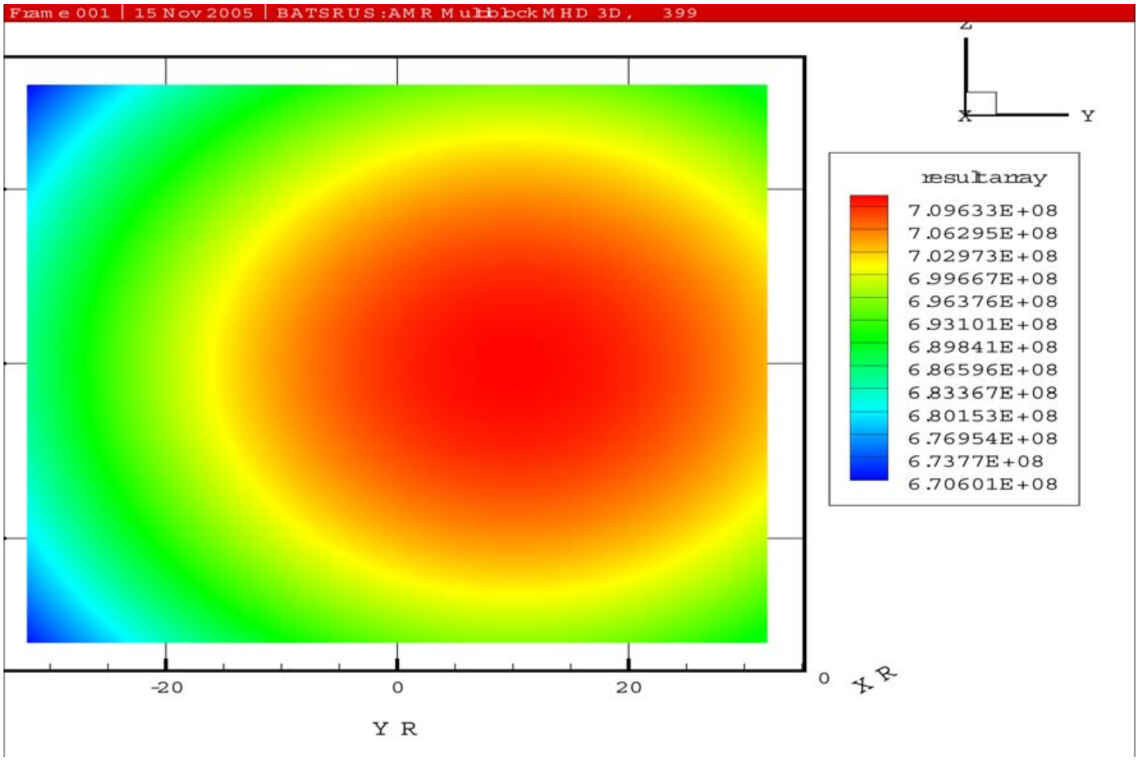

Figure 6: Raw image of a synthetic radio map

Despite these generally fitting features, the raw radio image does not show much further detail. This is no surprise, since there have been 216 cells considered only for the calculation of the convolution sum. We expect a much more detailed radio map, if we increase the number of cells that are superposed. This will be the next necessary developing step. Yet, with the number of cells increased, the computing time needed will also increase exponentially.