Preface

Calypso is a program package of magnetohydrodynamics (MHD) simulations in a rotating spherical shell for geodynamo problems. This package consists of the simulation program, preprocessing program, post processing program to generate field data for visualization programs, and several small utilities. The simulation program runs on parallel computing systems using MPI and OpenMP parallelization.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>6</td>
</tr>
<tr>
<td>History</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Updates for Ver 1.1</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Updates for Ver 1.2</td>
<td>8</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>9</td>
</tr>
<tr>
<td>Citation</td>
<td>9</td>
</tr>
<tr>
<td>Model of Simulation</td>
<td>10</td>
</tr>
<tr>
<td>5.1 Governing equations</td>
<td>10</td>
</tr>
<tr>
<td>5.2 Spherical harmonics expansion</td>
<td>12</td>
</tr>
<tr>
<td>5.3 Evaluation of Coriolis term</td>
<td>12</td>
</tr>
<tr>
<td>5.4 Boundary conditions</td>
<td>13</td>
</tr>
<tr>
<td>5.4.1 Non-slip boundary</td>
<td>13</td>
</tr>
<tr>
<td>5.4.2 Free-slip boundary</td>
<td>13</td>
</tr>
<tr>
<td>5.4.3 Fixed rotation rate</td>
<td>13</td>
</tr>
<tr>
<td>5.4.4 Fixed homogenous temperature</td>
<td>14</td>
</tr>
<tr>
<td>5.4.5 Fixed homogenous heat flux</td>
<td>14</td>
</tr>
<tr>
<td>5.4.6 Fixed composition</td>
<td>14</td>
</tr>
<tr>
<td>5.4.7 Fixed composition flux</td>
<td>14</td>
</tr>
<tr>
<td>5.4.8 Connection to the magnetic potential field</td>
<td>15</td>
</tr>
<tr>
<td>5.4.9 Magnetic boundary condition for center</td>
<td>16</td>
</tr>
<tr>
<td>5.4.10 Pseudo-vacuum magnetic boundary condition</td>
<td>16</td>
</tr>
<tr>
<td>Installation</td>
<td>17</td>
</tr>
<tr>
<td>6.1 Library Requirements</td>
<td>17</td>
</tr>
<tr>
<td>6.2 Known problems</td>
<td>18</td>
</tr>
<tr>
<td>6.3 Directories</td>
<td>18</td>
</tr>
<tr>
<td>6.4 Doxygen</td>
<td>19</td>
</tr>
<tr>
<td>6.5 Install using configure command</td>
<td>19</td>
</tr>
<tr>
<td>6.5.1 Configuration using configure command</td>
<td>19</td>
</tr>
<tr>
<td>6.5.2 Compile</td>
<td>21</td>
</tr>
<tr>
<td>6.5.3 Clean</td>
<td>22</td>
</tr>
<tr>
<td>6.5.4 Install</td>
<td>22</td>
</tr>
<tr>
<td>6.6 Install without using configure</td>
<td>22</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.7</td>
<td>Install using cmake</td>
</tr>
<tr>
<td>7</td>
<td>Simulation procedure</td>
</tr>
<tr>
<td>8</td>
<td>Examples</td>
</tr>
<tr>
<td>8.1</td>
<td>Examples for preprocessing program</td>
</tr>
<tr>
<td>8.2</td>
<td>Examples of dynamo benchmark</td>
</tr>
<tr>
<td>8.2.1</td>
<td>Data files and directories for Case 0</td>
</tr>
<tr>
<td>8.2.2</td>
<td>Data files and directories for Case 1</td>
</tr>
<tr>
<td>8.2.3</td>
<td>Data files and directories for Case 2</td>
</tr>
<tr>
<td>8.2.4</td>
<td>Data files and directories for Compositional Case 1</td>
</tr>
<tr>
<td>8.3</td>
<td>Example of data assembling program</td>
</tr>
<tr>
<td>8.4</td>
<td>Example of treatment of heat and composition source term</td>
</tr>
<tr>
<td>8.5</td>
<td>Example of thermal and compositional boundary conditions by external file</td>
</tr>
<tr>
<td>9</td>
<td>Preprocessing program (gen_sph_grid)</td>
</tr>
<tr>
<td>9.1</td>
<td>Position of radial grid</td>
</tr>
<tr>
<td>9.2</td>
<td>Control file (control_sph_shell)</td>
</tr>
<tr>
<td>9.3</td>
<td>Spectrum index data</td>
</tr>
<tr>
<td>9.4</td>
<td>Finite element mesh data</td>
</tr>
<tr>
<td>9.5</td>
<td>Radial grid data</td>
</tr>
<tr>
<td>9.6</td>
<td>How to define spatial resolution and parallelization?</td>
</tr>
<tr>
<td>10</td>
<td>Simulation program (sph_mhd)</td>
</tr>
<tr>
<td>10.1</td>
<td>Control file</td>
</tr>
<tr>
<td>10.2</td>
<td>Spectrum data for restarting</td>
</tr>
<tr>
<td>10.3</td>
<td>Thermal and compositional boundary condition data file</td>
</tr>
<tr>
<td>10.4</td>
<td>Field data for visualization</td>
</tr>
<tr>
<td>10.4.1</td>
<td>Distributed VTK data</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Merged VTK data</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Merged XDMF data</td>
</tr>
<tr>
<td>10.5</td>
<td>Cross section data (Parallel Surfacing module)</td>
</tr>
<tr>
<td>10.5.1</td>
<td>Control file</td>
</tr>
<tr>
<td>10.6</td>
<td>Isosurface data</td>
</tr>
<tr>
<td>10.6.1</td>
<td>Control file</td>
</tr>
<tr>
<td>10.7</td>
<td>Mean square amplitude data</td>
</tr>
<tr>
<td>10.7.1</td>
<td>Volume average data</td>
</tr>
<tr>
<td>10.7.2</td>
<td>Volume spectrum data</td>
</tr>
<tr>
<td>10.7.3</td>
<td>layered spectrum data</td>
</tr>
</tbody>
</table>
10.8 Gauss coefficient data [gauss_coef_prefix].dat .......... 58
10.9 Spectrum monitor data [picked_sph_prefix].dat .......... 59
10.10 Nusselt number data [nusselt_number_prefix].dat .... 59

11 Data transform program
(sph_snapshot and sph_zm_snapshot) 61

12 Initial field generation program
(sph_initial_field) 63
12.1 Definition of the initial field .......................... 64

13 Initial field modification program
(sph_add_initial_field) 67

14 Check program for dynamo benchmark
(sph_dynamobench) 68
14.1 Dynamo benchmark data dynamobench.dat ............... 69

15 Data assemble program (assemble_sph) 71
15.1 Format of control file ................................. 71

16 Module dependency program (module_dependency) 73

17 Time averaging programs 73
17.1 Averaging for mean square and power spectrum
(t_ave_sph_mean_square) ................................. 73
17.2 Averaging for picked harmonics mode data
(t_ave_picked_sph_coefs) ............................... 73

18 Visualization using field data

Appendices

Appendix A Definition of parameters for control files 78
A.1 data_files_def ........................................ 78
A.2 phys_values_ctl ....................................... 79
A.3 time_evolution_ctl .................................. 79
A.4 boundary_condition ................................ 79
A.5 forces_define ....................................... 83
A.6 dimensionless_ctl ................................. 83
A.7 coefficients_ctl ................................. 84
  A.7.1 thermal ..................................... 84
  A.7.2 momentum .................................. 84
  A.7.3 induction .................................. 85
  A.7.4 composition ................................ 86
A.8 temperature_define .............................. 86
A.9 time_step_ctl ................................... 87
A.10 new_time_step_ctl .............................. 88
A.11 restart_file_ctl ............................... 88
A.12 time_loop_ctl .................................. 89
A.13 sph_monitor_ctl ............................... 90
A.14 visual_control ................................. 93
A.15 cross_section_ctl .............................. 93
  A.15.1 surface_define ............................. 93
  A.15.2 output_field_define ....................... 95
  A.15.3 isosurf_define ............................ 96
  A.15.4 field_on_isosurf ......................... 97
A.16 num_domain_ctl ................................ 97
A.17 num_grid_sph .................................. 98
A.18 new_data_files_def ......................... 100
A.19 newrst_magne_ctl ............................ 100

Appendix B GNU GENERAL PUBLIC LICENSE ........................... 101
1 Introduction

Calypso is a program package for magneto-hydrodynamics (MHD) simulations in a rotating spherical shell for geodynamo problems. This package consists of the simulation program, preprocessing program, post processing program to generate field data for visualization programs, and several small utilities. The simulation program runs on parallel computing systems using MPI and OpenMP parallelization.

Calypso solves the equations that govern convection and magnetic-field generation in a rotating spherical shell. Flow is driven by thermal or compositional buoyancy in a Boussinesq fluid. Calypso also supports various boundary conditions (e.g. fixed temperature, heat flux, composition, and compositional flux), and permits a conductive and rotatable inner core. Results are written as spherical harmonics coefficients, Gauss coefficients for the region outside of the fluid shell, and field data in Cartesian coordinate for easy visualization with a number of visualization programs.

This user guide describes the essentials of the magnetohydrodynamics theory and equations behind Calypso, and provides instructions for the configuration and execution of Calypso.

2 History

Calypso has its origins in two earlier projects. One is a dynamo simulation code written by Hiroaki Matsui in 1990’s using a spectral method. This code solves for the poloidal and toroidal spectral coefficients, like Calypso, but it calculates the nonlinear terms in the spectral domain using a parallelization for SMP architectures. The other project is the thermal convection version of GeoFEM, which is Finite Element Method (FEM) platform for massively parallel computational environment, originally written by Hiroshi Okuda in 2000. Under GeoFEM Project, Lee Chen developed cross sectioning, iso-surfacing, and volume rendering modules for data visualization for parallel computations.

Hiroaki Matsui was responsible for adding routines to GeoFEM to perform magnetohydrodynamics simulation in a rotating frame. In 2002 this code successfully performed dynamo simulations in a rotating spherical shell using insulating magnetic boundary conditions. The following year Matsui implemented a subgrid scale (SGS) model in the FEM dynamo model in collaboration with Bruce Buffett. A module to solve for double diffusive convection was added to the FEM dynamo model by Hiroaki Matsui in 2009.

Progress in understanding the role of subgrid scale models in magnetohydrodynamic simulations relies on quantitative estimates for the transfer of energy between spatial scales. This information is most easily obtained from a spherical harmonic expansion of the simulation results, even when the simulation is performed by FEM. Hiroaki Matsui.
implemented the spherical harmonic transform in 2007 using a combination of MPI and OpenMP, and later included the spherical harmonic transform routines into his old dynamo code to create Calypso. Additional software in the program package for visualization is based on data formats from the FEM model. In addition, the control parameter file format is adapted from the input formats used in GeoFEM.

Calypso Ver. 1.0 supports the following features and capabilities

- Magnetohydrodynamics simulation for a Boussinesq fluid in a rotating spherical shell.
- Convection driven by thermal and compositional buoyancy.
- Temperature or heat flux is fixed at boundaries
- Composition or compositional flux is fixed at boundaries
- Non-slip or free-slip boundary conditions
- Outside of the fluid shell is electrically insulated or pseudo vacuum boundary.
- A conductive inner core with the same conductivity as the surrounding fluid
- A rotating inner core driven by the magnetic and viscous torques.

2.1 Updates for Ver 1.1

In Version 1.1, a number of bug fixes and additional comments for Doxygen are completed. The following large bugs are fixed:

- configure command is updated to find appropriate GNU make command. (see Section 6.1)

- Label for radial grid type in the file `ctl_sph_shell raidal_grid_type_ctl` is changed to `radial_grid_type_ctl`. If the old name is used in the control file, program `gen_sph_grid` will crash.

And, the following features are implemented

- New ordering is used for spherical harmonics data to reduce communication time. The old version of spectrum indexing data, which is generated by `gen_sph_grids` in Ver. 1.0 is also supported in Ver. 1.1.
• Evaluation of Coriolis term is updated. Now, Adams-Gaunt integrals are evaluated in the initialization process in the simulation program sph_mhd, so the data file for Adams-Gaunt integrals which is made by gen_sph_grids is not required.

• Add a program sph_add_initial_field. to modify existed initial field data. This program is used to modify or add new fields in spectrum data. (See Section 13)

• Heat and composition source terms are implemented. These source terms are fixed with time, and defined as spectrum data. The source terms are defined by using initial field generation program sph_initial_field or sph_add_initial_field. (See section 12 and 13)

• The boundary conditions for temperature and composition can be defined by using spherical harmonics coefficients. (i.e. inhomogeneous boundary conditions can be applied.) These boundary conditions are defined by using single external data file. (See Section 10.3)

### 2.2 Updates for Ver 1.2

In Version 1.2, the following features are implemented:

• To reduce the number of calculation, Legendre transform is calculated with taking account to the symmetry with respect to the equator. Time for Legendre transform is approximately half of that in Ver 1.1.

• BLAS library can be used for the Legendre transform optionally.

• Cross sectioning and isosurfacing module are newly implemented. These modules are re-written by Fortran90 from the parallel sectioning modules in GeoFEM by Lee Chen in C, and some features are added for visualizations of geodynamo simulations. See section ?? and 10.6

• Initial data assemble program assemble_mhd is parallelized. This program can perform with any number of MPI processes, but we recommend to run the program with one process or the same number of processes as the number of subdomains for the target configuration which is defined by num_new_domain_ctl. See section 13

• The time and time step information in the restart data can be modified by assemble_mhd. See section 13
3 Acknowledgements

Calypso was primarily developed by Dr. Hiroaki Matsui in collaboration with Prof. Bruce Buffett at the University of California, Berkeley. The following NSF grants supported the development of Calypso,

- B.A. Buffett and D. Lathrop, NSF EAR-0652882; CSED1 Collaborative Research: Integrating numerical and experimental geodynamo models, 2007 - 2009
- B.A. Buffett, NSF EAR-1045277; Development and application of turbulence models in numerical geodynamo simulations; 2010 - 2012

4 Citation

Computational Infrastructure for Geodynamics (CIG) and the Calypso developers are making the source code to Calypso available to researchers in the hope that it will aid their research and teaching. A number of individuals have contributed a significant amount of time and energy into the development of Calypso. We request that you cite the appropriate papers and make acknowledgements as necessary. The Calypso development team asks that you cite the following papers:

Matsui, H., E. King, and B.A. Buffett, Multi-scale convection in a geodynamo simulation with uniform heat flux along the outer boundary, Geochemistry, Geophysics, Geosystems, 15, 3212 – 3225, 2014.
5 Model of Simulation

5.1 Governing equations

This model performs a magnetohydrodynamics (MHD) simulation in a rotating spherical shell modeled on the Earth’s outer core (see Figure 1). We consider a spherical shell from the inner core boundary (ICB) to the core mantle boundary (CMB) in a rotating frame which constantly rotates with angular velocity \( \Omega = \Omega \hat{z} \). The fluid shell is filled with a conductive fluid with constant diffusivities (kinematic viscosity \( \nu \), magnetic diffusivity \( \eta \), thermal diffusivity \( \kappa_T \), and compositional diffusivity \( \kappa_C \)). The inner core (\( 0 < r < r_i \)) is solid, and may be considered an electrical insulator or may have the same conductivity as the outer core. We assume that the region outside of the core is an electrical insulator. The rotating spherical shell is filled with Boussinesq modeled fluid. The governing equations of the MHD dynamo problem are the following,

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \times \mathbf{u}) = -\nabla \left( P + \frac{1}{2} u^2 \right) - \nu \nabla \times \nabla \times \mathbf{u} - 2\Omega (\hat{z} \times \mathbf{u}) + \left( \frac{\rho}{\rho_0} \mathbf{g} \right) + \frac{1}{\rho_0} (\mathbf{J} \times \mathbf{B}) ,
\]
\[
\frac{\partial B}{\partial t} = -\eta \nabla \times \nabla \times B + \nabla \times (u \times B),
\]
\[
\frac{\partial T}{\partial t} + (u \cdot \nabla) T = \kappa_T \nabla^2 T + q_T,
\]
\[
\frac{\partial C}{\partial t} + (u \cdot \nabla) C = \kappa_C \nabla^2 C + q_C,
\]
\[
\nabla \cdot u = \nabla \cdot B = 0,
\]
\[
\omega = \nabla \times u,
\]
and
\[
J = \frac{1}{\mu_0} \nabla \times B,
\]
where, \( u, \omega, P, B, J, T, C, q_T, \) and \( q_C \) are the velocity, vorticity, pressure, magnetic field, current density, temperature, compositional variation, heat source, and source of light element, respectively. Coefficients in the governing equations are the kinetic viscosity \( \nu \), thermal diffusivity \( \kappa_T \), compositional diffusivity \( \kappa_C \), and magnetic diffusivity \( \eta \). The density \( \rho \) is written as a function of \( T, C, \) average density \( \rho_0 \), thermal expansion \( \alpha_T \), and density ratio of light element to main composition \( \alpha_C \),
\[
\rho = \rho_0 [1 - \alpha_T (T - T_0) - \alpha_C (C - C_0)]
\]
In Calypso, the vorticity equation and divergence of the momentum equation are used for solving \( u, \omega, \) and \( P \) as,
\[
\frac{\partial \omega}{\partial t} + \nabla \times (\omega \times u) = -\nu \nabla \times \nabla \times \omega - 2\Omega \nabla \times (\hat{z} \times u)
\]
\[
+ \nabla \times \left( \frac{\rho}{\rho_0} g \right) + \frac{1}{\rho_0} \nabla \times (J \times B),
\]
and
\[
\nabla \cdot (\omega \times u) = -\nabla^2 \left( P + \frac{1}{2} u^2 \right) - 2\Omega \nabla \cdot (\hat{z} \times u)
\]
\[
+ \nabla \cdot \left( \frac{\rho}{\rho_0} g \right) + \frac{1}{\rho_0} \nabla \cdot (J \times B).
\]
5.2 Spherical harmonics expansion

In Calypso, fields are expanded into spherical harmonics. A scalar field (for example, temperature $T(r, \theta, \phi)$) is expanded as

$$T(r, \theta, \phi) = \sum_{l=0}^{L} \sum_{m=-l}^{l} T_l^m(r) Y_l^m(\theta, \phi),$$

where $Y_l^m$ are the spherical harmonics. Solenoidal fields (e.g. velocity $u$, vorticity $\omega$, magnetic field $B$, and current density $J$) are decomposed into poloidal and toroidal components. For example, the magnetic field is described as

$$B(r, \theta, \phi) = \sum_{l=1}^{L} \sum_{m=-l}^{l} (B_{Sl}^m + B_{Tl}^m),$$

where

$$B_{Sl}^m(r, \theta, \phi) = \nabla \times \nabla \times (B_{sl}^m(r) Y_l^m(\theta, \phi) \hat{r}),$$

$$B_{Tl}^m(r, \theta, \phi) = \nabla \times (B_{tl}^m(r) Y_l^m(\theta, \phi) \hat{r}).$$

The spherical harmonics are defined as real functions. $P_m^m \cos(m\phi)$ is assigned for positive $m$, $P_m^m \sin(m\phi)$ is assigned for negative $m$, where $P_l^m$ are Legendre polynomials. Because Schmidt quasi normalization is used for the Legendre polynomials $P_l^m$, the orthogonality relation for the spherical harmonics is

$$\int Y_l^m Y_{l'}^m \sin \theta d\theta d\phi = 4\pi \frac{1}{2l+1} \delta_{ll'} \delta_{mm'},$$

where, $\delta_{ll'}$ is Kronecker delta.

5.3 Evaluation of Coriolis term

The curl of the Coriolis force $-2\Omega \nabla \times (\hat{z} \times u)$ is evaluated in the spectrum space using the triple products of the spherical harmonics. These 3j-symbols (or Gaunt integral $G_{Lll'}^{Mmm'}$ and Elsasser integral $E_{Lll'}^{Mmm'}$) are written as

$$G_{Lll'}^{Mmm'} = \int Y_L^M Y_l^m Y_{l'}^{m'} \sin \theta d\theta d\phi,$$

$$E_{Lll'}^{Mmm'} = \int Y_L^M \left( \frac{\partial Y_l^m}{\partial \theta} \frac{\partial Y_{l'}^{m'}}{\partial \phi} - \frac{\partial Y_l^m}{\partial \phi} \frac{\partial Y_{l'}^{m'}}{\partial \theta} \right) d\theta d\phi.$$

The Gaunt integral $1/(4\pi) G_{Lll'}^{Mmm'}$ and Elsasser integral $1/(4\pi) E_{Lll'}^{Mmm'}$ for the Coriolis terms are evaluated in the simulation program.
5.4 Boundary conditions

Calypso currently supports the following boundary conditions for velocity $u$, magnetic field $B$, temperature $T$, and composition variation $C$. These boundary conditions are defined in the control file `control_MHD`.

5.4.1 Non-slip boundary

The velocity $u$ is set to be 0 at the boundary. For poloidal and toroidal coefficients of velocity, $U_{Sl}^m(r)$ and $U_{Tl}^m(r)$, the boundary condition can be described as

$$ U_{Sl}^m(r) = \frac{\partial U_{Sl}^m}{\partial r} = 0, $$

and

$$ U_{Tl}^m(r) = 0. $$

5.4.2 Free-slip boundary

For a free slip boundary, shear stress and radial flow vanish at the boundary. The boundary condition for poloidal and toroidal coefficients are described as

$$ U_{Sl}^m(r) = \frac{\partial^2}{\partial r^2} \left( \frac{1}{r} U_{Sl}^m(r) \right) = 0, $$

and

$$ \frac{\partial}{\partial r} \left( \frac{1}{r^2} U_{Tl}^m(r) \right) = 0. $$

5.4.3 Fixed rotation rate

If the boundary rotates with a rotation vector $\Omega_b = (\Omega_{bx}, \Omega_{by}, \Omega_{bz})$, the boundary conditions for poloidal and toroidal coefficients are described as

$$ U_{Sl}^m(r) = \frac{\partial U_{Sl}^m}{\partial r} = 0, $$

$$ U_{Tl}^{1s}(r) = r^2 \Omega_{by}, $$

$$ U_{Tl}^{0}(r) = r^2 \Omega_{bz}, $$

$$ U_{Tl}^{1c}(r) = r^2 \Omega_{bx}, $$

and

$$ U_{Tl}^m(r) = 0 \text{ for } l > 2. $$
5.4.4 Fixed homogenous temperature

When a constant temperature $T_b$ is applied, the spherical harmonic coefficients are

$$ T^0_0(r) = T_b, $$

and

$$ T^m_l(r) = 0 \text{ for } l > 1. $$

5.4.5 Fixed homogenous heat flux

A constant heat flux is imposed by setting the radial temperature gradient to $F_{Tb}$. The spherical harmonic coefficients are

$$ \frac{\partial T^0_0}{\partial r} = F_{Tb}, $$

and

$$ \frac{\partial T^m_l}{\partial r} = 0 \text{ for } l > 1. $$

5.4.6 Fixed composition

When a constant composition $C_b$ is applied, the spherical harmonic coefficients are

$$ C^0_0(r) = C_b, $$

and

$$ C^m_l(r) = 0 \text{ for } l > 1. $$

5.4.7 Fixed composition flux

A constant composition flux is imposed by setting the radial composition gradient to $F_{Cb}$. The spherical harmonic coefficients are

$$ \frac{\partial C^0_0}{\partial r} = F_{Cb}, $$

and

$$ \frac{\partial C^m_l}{\partial r} = 0 \text{ for } l > 1. $$
5.4.8 Connection to the magnetic potential field

If the regions outside the fluid shell are assumed to be electrical insulators, current density vanishes in the electric insulator

\[ J_{\text{ext}} = 0, \]

where the suffix \( \text{ext} \) indicates fields outside of the fluid shell. At the boundaries of the fluid shell, the magnetic field \( B_{\text{fluid}} \), current density \( J_{\text{fluid}} \), and electric field \( E_{\text{fluid}} \) in the conductive fluid satisfy:

\[
(B_{\text{fluid}} - B_{\text{ext}}) = 0,
\]

\[
(J_{\text{fluid}} - J_{\text{ext}}) \cdot \hat{r} = 0,
\]

and

\[
(E_{\text{fluid}} - E_{\text{ext}}) \times \hat{r} = 0,
\]

where, \( \hat{r} \) is the radial unit vector (i.e. normal vector for the spherical shell boundaries). Consequently, radial current density \( J \) vanishes at the boundary as

\[ J \cdot \hat{r} = 0 \text{ at } r = r_i, r_o \]

In an electrical insulator the magnetic field can be described as a potential field

\[ B_{\text{ext}} = -\nabla W_{\text{ext}}, \]

where \( W_{\text{ext}} \) is the magnetic potential. The boundary conditions can be satisfied by connecting the magnetic field in the fluid shell at boundaries to the potential fields. The magnetic field is connected to the potential field in an electrical insulator. At CMB \( (r = r_o) \), the boundary condition can be described by the poloidal and toroidal coefficients of the magnetic field as

\[
\frac{l}{r} B_{\text{Sl}}^m(r) = -\frac{\partial B_{\text{Sl}}^m}{\partial r},
\]

and

\[ B_{Tl}^m(r) = 0. \]

If the inner core is also assumed to be an insulator, the magnetic boundary conditions for ICB \( (r = r_i) \) can be described as

\[
\frac{l + 1}{r} B_{\text{Sl}}^m(r) = \frac{\partial B_{\text{Sl}}^m}{\partial r},
\]

and

\[ B_{Tl}^m(r) = 0. \]
5.4.9 Magnetic boundary condition for center

If the inner core has the same conductivity as the outer core, we solve the induction equation for the inner core as for the outer core with the boundary conditions for the center. The poloidal and toroidal coefficients at center are set to

\[ B_{SI}^m(0) = B_{TI}^m(0) = 0. \]

5.4.10 Pseudo-vacuum magnetic boundary condition

Under the pseudo-vacuum boundary condition, the magnetic field has only a radial component at the boundaries. Considering the conservation of the magnetic field, the magnetic boundary condition will be

\[ \frac{\partial}{\partial r} \left( r^2 B_r \right) = B_\theta = B_\phi = 0 \text{ at } r = r_i, r_o. \]

The present boundary condition is also described by using the poloidal and toroidal coefficients as

\[ \frac{\partial B_{SI}^m}{\partial r} = B_{TI}^m(r) = 0 \text{ at } r = r_i, r_o. \]
6 Installation

6.1 Library Requirements

Calypso requires the following libraries.

- GNU make
- MPI libraries (OpenMPI, MPICH, etc)
- FFTPACK Ver 5.1D (http://people.sc.fsu.edu/~jburkardt/f_src/fftpack5.1d/fftpack5.1d.html). The source files for FFTPACK are included in src/EXTERNAL_libs directory.

Linux and Max OS X use GNU make as a default ‘make’ command, but some system (e.g. BSD or SOLARIS) does not use GNU make as default. configure command searches and set correct GNU make command.

In addition, the following environment and libraries can be used (optional).

- OpenMP
- BLAS
- FFTW version 3 (http://www.fftw.org) including Fortran wrapper
- PARALLEL HDF5 (http://www.hdfgroup.org/HDF5/PHDF5) including Fortran wrapper.

Note: Calypso does NOT use MPI and OpenMP features in FFTW3.

In the most of platforms, the Fourier transform by FFTW is faster than that by FFTPACK.

HDF5 is used for field data output with XDMF format instead of VTK format. The comparison of field data format is described in section refsec:VTK.

OpenMP is used for the parallelization under the shared memory. Better choice to use both MPI and OpenMP parallelization (so-called Hybrid parallelization) or only using MPI (so-called flat MPI) is depends on the computational platform and compiler. For example, flat MPI has much better performance on Linux cluster with Intel Xeon processors and with Intel fortran compiler, but Hybrid model has better performance on Hitachi SR16000 with Power 6 processors.
6.2 Known problems

**FFTPACK and Intel compiler**

FFTPACK fails to compile with Intel fortran using the ‘-warn all’ option. Currently the ‘-warn all’ option is excluded by Makefile when FFTPACK is compiled.

**Homebrew’s FFTW3 on Mac OS X**

Calypso uses Fortran wrappers in FFTW3. If FFTW3 is installed using Homebrew for Mac OS X ([http://mxcl.github.com/homebrew/](http://mxcl.github.com/homebrew/)), the required fortran wrappers are not installed. In this case, please install FFTW3 with Fortran wrappers with another package manager (Macports ([http://www.macports.org](http://www.macports.org)), for example), build FFTW3 by yourself including the Fortran wrapper, or turn off FFTW3 features in Calypso.

**XL fortran**

In XL fortran, preprocessor options is not specified by -D..., but -Wf, ‘-D...’. Please edit preprocessor macro option F90CPPFLAGS in work/Makefile by an editor.

**Cross compiler support**

configure command in Calypso does not support cross compilation. If you want to compile with a cross compiler, please set the variables in Makefile manually (see section 6.6)

6.3 Directories

The top directory of Calypso (ex. [CALYPSO_HOME]) contains the following directories.

```
% cd [CALYPSO_HOME]
% ls
CMakeLists.txt Makefile.in configure.in examples
INSTALL bin doc src
LICENSE configure doxygen work
```

**bin:** directory for executable files

**cmake:** directory for cmake configurations
Doxygen \(^{(\text{http://www.doxygen.org})}\) is a powerful document generation tool from source files. We only save a configuration file in this directory because thousands of html files generated by doxygen. The documents for source codes are generated by the following command:

\[
\% \text{ cd } [\text{CALYPSO\_HOME}]/\text{doxygen} \\
\% \text{ doxygen } ./\text{Doxyfile\_CALYPSO}
\]

The html documents can be seen by opening \([\text{CALYPSO\_HOME}]/\text{doxygen/html/index.html}\). Automatically generated documentation is also available on the CIG website at \(\text{http://www.geodynamics.org/cig/software/calypso/}\).

**6.5 Install using `configure` command**

**6.5.1 Configuration using `configure` command**

Calypso uses the configure script for configuration to install. The simplest way to install programs is the following process in the top directory of Calypso.

\[
\% \text{ pwd} \\
[\text{CALYPSO\_HOME}] \\
\% ./\text{configure} \\
... \\
\% \text{ make} \\
... \\
\% \text{ make install}
\]

After the installation, object modules can be deleted by the following command:

\[
\% \text{ make clean}
\]
configure generates a Makefile in the current directory. Available options for configure can be checked using the ./configure --help command. The following options are available in the configure command.

Optional Features:
--disable-option-checking ignore unrecognized --enable/--with options
--disable-FEATURE do not include FEATURE (same as --enable-FEATURE=no)
--enable-FEATURE[=ARG] include FEATURE [ARG=yes]
--enable-fftw3 Use fftw3 library

Optional Packages:
--with-PACKAGE[=ARG] use PACKAGE [ARG=yes]
--without-PACKAGE do not use PACKAGE (same as --with-PACKAGE=no)
--with-hdf5=yes/no/PATH full path of h5pcc for parallel HDF5 configuration
--with-blas=<lib> use BLAS library <lib>

Some influential environment variables:
CC C compiler command
CFLAGS C compiler flags
LDFLAGS linker flags, e.g. -L<lib dir> if you have libraries in a nonstandard directory <lib dir>
LIBS libraries to pass to the linker, e.g. -l<library>
CPPFLAGS (Objective) C/C++ preprocessor flags, e.g. -I<include dir> if you have headers in a nonstandard directory <include dir>
FC Fortran compiler command
FCFLAGS Fortran compiler flags
MPICC MPI C compiler command
MPIFC MPI Fortran compiler command
PKG_CONFIG path to pkg-config utility
CPP C preprocessor
FFTW3_CFLAGS C compiler flags for FFTW3, overriding pkg-config
FFTW3_LIBS linker flags for FFTW3, overriding pkg-config

An example of usage of the configure command is the following:

```bash
% ./configure --prefix=/Users/matsui/local \
  ? CFLAGS=-O -Wall -g FCFLAGS=-O -Wall -g \
  ? PKG_CONFIG_PATH=/Users/matsui/local/lib/pkgconfig \
  ? --enable-fftw3 --with-hdf5=/Users/matsui/local/bin/h5pcc
```
6.5.2 Compile

Compile is performed using the `make` command. The Makefile in the top directory is used to generate another Makefile in the `work` directory, which is automatically used to complete the compilation. The object file and libraries are compiled in the `work` directory. Finally, the executive files are assembled in `bin` directory. You should find the following programs in the `bin` directory.

- **gen_sph_grids**: Preprocessing program for data transfer for spherical transform
- **sph_mhd**: Simulation program
- **sph_initial_field**: Example program to generate initial field
- **sph_add_initial_field**: Example program to add initial field in existing spectrum data
- **sph_snapshot**: Data transfer from spectrum data to field data
- **sph_dynamobench**: Data processing for dynamo benchmark test by Christensen *et al.* (2002)
- **sph_zm_snapshot**: Generate zonal mean field
- **assemble_sph**: Data transfer program to change number of subdomains.
- **t_ave_sph_mean_square**: Time averaging program for the mean square data.
- **t_ave_picked_sph_coefs**: Time averaging program for the picked spectrum data.
- **t_ave_nusselt**: Time averaging program for the Nusselt number data.
- **check_sph_grids**: Check program for tests.
- **make_f90depends**: Program to generate dependency of the source code (*make command uses to generate work/Makefile*)

The following library files are also made in `work` directory.

- **libcalypso.a**: Calypso library
- **libfftpack.5d.a**: FFTPACK 5.1 library
6.5.3 Clean

The object and fortran module files in work directory is deleted by typing

% make clean

This command deletes files with the extension .o, .mod, .par, .diag, and .

6.5.4 Install

The executive files are copied to the install directory $(INSTDIR)/bin. The install directory $(INSTDIR) is defined in Makefile, and can also set by ${--prefix} option for configure command. Alternatively, you can use the programs in ${SRCDIR}/bin directory without running make install. If directory ${PREFIX} does not exist, make install creates ${PREFIX}, ${PREFIX}/lib, ${PREFIX}/bin, and ${PREFIX}/include directories. No files are installed in ${PREFIX}/lib and ${PREFIX}/include.

6.6 Install without using configure

It is possible to compile Calypso without using the configure command. To do this, you need to edit the Makefile. First, copy Makefile from template Makefile.in as

% cp Makefile.in Makefile

In Makefile, the following variables should be defined.

SHELL Name of shell command.

SRCDIR Directory of this Makefile.

INSTDIR Install directory.

MPICHDIR Directory names for MPI implementation. If you set fortran90 compiler name for MPI programs in MPIF90, you do not need to define this valuable.

MPICHINCDIR Directory names for include files for MPI implementation. If you set fortran90 compiler name for MPI programs in MPIF90, you do not need to define this valuable.

MPILIBS Library names for MPI implementation. If you set fortran90 compiler name for MPI programs in MPIF90, you do not need to define this valuable.
**F90_LOCAL** Command name of local Fortran 90 compiler to compile module dependency listing program.

**MPIF90** Command name of Fortran90 compiler and linker for MPI programs. If command does not have MPI implementation, you need to define the definition of MPI libraries MPICHDIR, MPICHINCDIR, and MPILIBS.

**AR** Command name for archive program (ex. ar) to generate libraries. If you need some options for archive command, options are also included in this valuable.

**RANLIB** Command name for ranlib to generate index to the contents of an archive. If system does not have ranlib, set true in this valuable. true command does not do anything for libraries.

**F90OPTFLAGS** Optimization flags for Fortran90 compiler (including OpenMP flags)

**FFTW3_CFLAGS** Option flags for FFTW3 (ex. -I/usr/local/include)

**FFTW3_LIBS** Library lists for FFTW3 (ex. -L/usr/local/lib -lfftw3 -lm)

**HDF5_FFLAGS** Option flags to compile with HDF5. This setting can be found by using hfd5 command h5pfc -show.

**HDF5_LDFLAGS** Option flags to link with HDF5. This setting can be found by using hfd5 command h5pfc -show.

**HDF5_FLIBS** Library lists for HDF5. This setting can be found by using hfd5 command h5pfc -show.

### 6.7 Install using cmake

CMake is a cross-platform, open-source build system. CMake can be downloaded from [http://www.cmake.org](http://www.cmake.org). The following procedure is required to install.

1. Create working directory (you can also use [CALYPSO_HOME]/work).

2. Generate Makefile and working directories by cmake command.

3. Compile programs by make command.
In this section, \[\text{CALYPSO\_HOME}/\text{work}\] is used as the working directory. Options for CMake can be checked by `cmake -i \[\text{CALYPSO\_HOME}\]` command at \[\text{CALYPSO\_HOME}/\text{work}\]. There are a number of options can be found, but the following valuables are important settings for installation:

- **CMAKE_INSTALL_PREFIX** Install directory
- **CMAKE_Fortran_COMPILER** Fortran90 compiler.
- **CMAKE_DISABLE_FIND_PACKAGE_OpenMP_Fortran** OpenMP is not used if ’yes’ is set in this valuable.
- **CMAKE_DISABLE_FIND_PACKAGE_FFTW** FFTW3 library does not linked if ’yes’ is set in this valuable.
- **CMAKE_LIBRARY_PATH** CMake library search paths. This directory is used to search FFTW3 library.
- **CMAKE_INCLUDE_PATH** CMake include search paths. This directory is used to search include file for FFTW3.
- **CMAKE_DISABLE_FIND_PACKAGE_FFTW** FFTW3 library does not linked if ’yes’ is set in this valuable.
- **HDF5_INCLUDE_DIRS** Include file directories to compile with HDF5. This setting can be found by using `hfd5` command `h5pfc -show`.
- **HDF5_LIBRARY_DIRS** Location of HDF5 library. This setting can be found by using `hfd5` command `h5pfc -show`.
- **HDF5_LIBRARIES** Library lists for HDF5. This setting can be found by using `hfd5` command `h5pfc -show`.
- **CMAKE_DISABLE_FIND_PACKAGE_HDF5** HDF5 library does not linked if ’yes’ is set in this valuable.

An example of using CMake on Mac OS X is the following:

```bash
% cd work
% h5pfc -show
mpif90 -I/home/matsui/local/include -L/home/matsui/local/lib /home/matsui/local/lib/ libhdf5hl_fortran.a /home/matsui/local/lib/libhdf5_hl.a
```
/home/matsui/local/lib/libhdf5_fortran.a
/home/matsui/local/lib/libhdf5.a
  -L/home/matsui/local/lib -lmpi -lz -ldl -lm
% cmake .. -DCMAKE_LIBRARY_PATH='/home/matsui/local/lib' \
? -DCMAKE_INCLUDE_PATH='/home/matsui/local/include' \
? -DHDF5_INCLUDE_DIRS='/home/matsui/local/include' \
? -DHDF5_LIBRARY_DIRS='/home/matsui/local/lib' \
? -DHDF5_LIBRARIES='/home/matsui/local/lib/libhdf5hl_fortran.a \
? /home/matsui/local/lib/libhdf5_hl.a \
? /home/matsui/local/lib/libhdf5_fortran.a \
? /home/matsui/local/lib/libhdf5.a'

After configuration, compile and install are started by

% make
...% make install

After running make command, execute files are built in [CALYPSO_HOME]/work/bin directory.

7 Simulation procedure

Calypso consists of programs shown in Table 1. Because the serial programs do not use MPI, they are simply invoked by

% [program]

Parallel programs must be invoked using MPI commands. On a Linux cluster using MPICH, parallel programs are invoked with

% mpirun -np [# of processes] [program]

This command will vary depending on the MPI implementation installed on the machine. Please consult with your sysadmin for details.

To perform simulations by Calypso, the following processes are required.

1. Generate grids and spherical harmonics indexing information by gen_sph_grids.

2. Make initial fields by sph_initial_field (if necessary).
Table 1: List of program and required control file name

<table>
<thead>
<tr>
<th>Program</th>
<th>Control file name</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>gen_sph_grids</td>
<td>control_sph_shell</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_mhd</td>
<td>control_MHD</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_initial_field</td>
<td>control_MHD</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_add_initial_field</td>
<td>control_MHD</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_snapshot</td>
<td>control_snapshot</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_zm_snapshot</td>
<td>control_snapshot</td>
<td>Parallel</td>
</tr>
<tr>
<td>sph_dynamobench</td>
<td>control_snapshot</td>
<td>Parallel</td>
</tr>
<tr>
<td>assemble_sph</td>
<td>control_sph_assemble</td>
<td>Parallel</td>
</tr>
<tr>
<td>t_ave_sph_mean_square</td>
<td>N/A</td>
<td>Serial</td>
</tr>
<tr>
<td>t_ave_picked_sph_coefs</td>
<td>N/A</td>
<td>Serial</td>
</tr>
<tr>
<td>t_ave_nusselt</td>
<td>N/A</td>
<td>Serial</td>
</tr>
</tbody>
</table>

3. Perform the simulation by sph_mhd.

4. Convert the parallel spectra data by assemble_sph to continue with changing number of processes (if necessary).

5. Data analysis by sph_snapshot, sph_snapshot, or sph_dynamobench.

6. Update initial fields by sph_add_initial_field for more simulations (if necessary).

7. Evaluate time averages by t_ave_sph_mean_square, t_ave_picked_sph_coefs, or t_ave_nusselt if necessary.

The simulation program sph_mhd requires an indexing file for spherical transform. sph_mhd generates spectrum data and monitoring data, and field data in Cartesian coordinate as outputs. The data transform programs (sph_snapshot and sph_zm_snapshot) generate outputs data from parallel spectra data. The flow of data is shown in Figure 2.
Figure 2: Data flow of the simulation. Simulations require index data for spherical harmonics transform, initial spectra (optional) data, and FEM mesh data. Simulation program also outputs spectra data, monitoring data and field data in Cartesian coordinate. Data transform program generates output data for simulation program from spectra data.

Each program needs one control file, the name of which is defined by the program. (Standard input is not supported by Fortran 90 so Calypso uses control files.) The appropriate control file names are shown in the Table 1. The following rules are used in the control files. An example of a control file is shown in Figure 3.

- Lines starting with ‘#’ or ‘!’ are treated as a comment lines and ignored.
- All control files consist of blocks which start with ‘begin [name]’ and end with ‘end [name]’.
- The item name is shown first and the associated value/data is second.
- The order of items and blocks can be changed.
- If an item consists of multiple data, these should be listed in one line.
- If an item does not belong in the block it is ignored.
- An array block starts with ‘begin array [name] [number of components]’ and ends with ‘end array [name]’.
- If [number of components] for an array is 0, ‘end array [name]’ on the next line is not needed.
• In Fortran program, character ‘/’ is recognized as an end of character valuable if text with ‘/’ (e.g. file prefix including file paths) is not enclosed by ‘’ or “”.

• Calypso’s control file input is limited to 255 characters for each line.

```fortran
begin spherical_shell_ctl
  !
  begin data_files_def
    num_subdomain_ctl 4
    !
    sph_file_prefix 'sph_shell/in'
  end data_files_def
  !
  begin num_grid_sph
    truncation_level_ctl 4
    ngrid_meridonal_ctl 12
    ngrid_zonal_ctl 24
    !
    radial_grid_type_ctl explicit
    array r_layer 4
      r_layer 1 0.5384615384615
      r_layer 2 0.5384615384615
      r_layer 3 1.038461538462
      r_layer 4 1.538461538462
    end array r_layer
    !
  end num_grid_sph
end spherical_shell_ctl
```

Figure 3: Example of Control file
8 Examples

Several examples are provided in the examples directory. There are three subdirectories as examples. README files are also provided to perform these examples in each subdirectory.

assemble_sph Examples for assembling program of spectrum data. (see section 15)
dynamo_benchmark Examples for dynamo benchmark by Christensen et. al. (2001)
heat_composition_source Examples for the heat and composition diffusion problem including source term
heterogeneous_temp Examples for the heat and composition diffusion problem including thermal and compositional heterogeneity at boundaries.
spherical_shell Examples for preprocessing program (see Section 9)

8.1 Examples for preprocessing program

Four examples illustrate the use of the preprocessing program. The examples include

Chebyshev_points Example to generate indexing data using Chebyshev collocation points
equidistance Example to generate indexing data with equi-distance grid
explicitly_defined Example to generate indexing data with explicitly defined radial points
with_inner_core Example to generate indexing data including inner core and external of the fluid shell.

The program gen_sph_grids generate spherical harmonics indexing file under the directory defined by the file control_sph_shell.

8.2 Examples of dynamo benchmark

There are four examples for simulations using dynamo benchmark test as following.

Case_0 Example of dynamo benchmark case 0 (Thermally driven convection without magnetic field)
Case_1 Example of dynamo benchmark case 1 (Dynamo model with co-rotating and electrically insulated inner core)

Case_2 Example of dynamo benchmark case 2 (Dynamo model with rotatable and conductive inner core)

Compositional_case_1 Example of dynamo benchmark case 1 using compositional variation instead of temperature

The process of the simulation in these examples is the same using 4 MPI processes:

1. Change to the directory for Benchmark Case 1 (for example)

   [username]$ cd [CALYPSO_DIR]/examples/dynamo_benchmark/dynamobench_case1

2. Create the grid files for the simulation

   [dynamobench_case_1]$ [CALYPSO_DIR]/bin/gen_sph_grids

3. Create initial field (Benchmark Case 1 only, see section 12)

   [dynamobench_case_1]$ [CALYPSO_DIR]/bin/sph_initial_field

4. Run simulation program

   [dynamobench_case_1]$ mpirun -np 4 [CALYPSO_DIR]/bin/sph_mhd

5. To continue the simulation, change the parameter rst_ctl in control_MHD from dynamo_benchmark_1 to start_from_RST_file and continue simulation by repeating step 2.

6. To check the results for dynamo benchmark, run

   [dynamobench_case_1]$ mpirun -np 4 [CALYPSO_DIR]/bin/sph_dynamobench

Each example has the following input and data outputs.
8.2.1 Data files and directories for Case 0

control_sph_shell Control file for spherical shell preprocessing
control_MHD Control file for simulation
control_snapshot Control file for postprocessing
sph_lm31r48c_4 Spherical shell indexing data directory
rst_4 Spectr data directory for restarting
field Field data directory for for visualization
sections Cross section data directory for for visualization

8.2.2 Data files and directories for Case 1

control_sph_shell Control file for spherical shell preprocessing
control_MHD Control file for simulation
control_snapshot Control file for postprocessing
control_psf_CMB Control file for section at CMB (See Section 10.5)
control_psf_eq Control file for section at equatorial plane (See Section 10.5)
control_psf_z0.3 Control file for section at z = 0.3 (See Section 10.5)
control_psf_s0.5 Control file for cylindrical surface at s = 0.55 (See Section 10.5)
control_iso_temp Control file for isosurface of temperature (See Section 10.6)
sph_lm31r48c_4 Spherical shell indexing data directory
rst_4 Spectr data directory for restarting
field Field data directory for for visualization
field Field data directory for for visualization
sections Cross section data directory for for visualization (See Section 10.5)
isosurfaces Isosurface data directory for for visualization (See Section 10.6)

After running the program, the following files are written.
sph_pwr_volume_s.dat Mean square data over the fluid shell.
8.2.3 Data files and directories for Case 2

control_sph_shell Control file for spherical shell preprocessing
control_MHD Control file for simulation
control_snapshot Control file for postprocessing
control_psf_CMB Control file for section at CMB (See Section 10.5)
control_psf_ICB Control file for section at ICB (See Section 10.5)
control_psf_eq Control file for section at equatorial plane (See Section 10.5)
control_psf_z0.3 Control file for section at z = 0.3 (See Section 10.5)
control_psf_s0.55 Control file for cylindrical surface at s = 0.55 (See Section 10.5)
sph_lm31r48c_4 Spherical shell indexing data directory
rst_4 Spectr data directory for restarting
field Field data directory for visualization
sections Cross section data directory for visualization (See Section 10.5)

After running the program, the following files are written.
sph_pwr_volume_s.dat Mean square data over the fluid shell.

8.2.4 Data files and directories for Compositional Case 1

const_sph_initial_spectr.f90 Source code to generate initial field (need )
control_sph_shell Control file for spherical shell preprocessing
control_MHD Control file for simulation
control_snapshot Control file for postprocessing
sph_lm31r48c_4 Spherical shell indexing data directory
rst_4 Spectr data directory for restarting
field Field data directory for visualization
8.3 Example of data assembling program

An example for spectrum data assembling program is provided in assemble_sph directory. This example uses simulation results of dynamo benchmark case 1. First, copy data from dynamo benchmark case 1 as

```
[assemble_sph]$ cp ../dynamo_benchmark/dynamobench_case_1/sph_lm31r48c_4/* sph_lm31r48c_4/
[assemble_sph]$ cp ../dynamo_benchmark/dynamobench_case_1/rst_4/rst.* 4domains/
```

Then, construct new domain decomposition data as

```
[sph_lm31r48c_4]$ sph_lm31r48c_2
[sph_lm31r48c_2]$ [CALYPSO_DIR]/bin/gen_sph_grids
[sph_lm31r48c_2]$ cd ../
```

Finally restart data for new configuration is generated by assemble_sph in 2doamins directory.

```
[sph_lm31r48c_2]$ [CALYPSO_DIR]/bin/assemble_sph
```

8.4 Example of treatment of heat and composition source term

This example solves heat and composition diffusion with including source terms. In this example, only temperature and composition are solved by

\[
\frac{\partial T}{\partial t} = \kappa_T \nabla^2 T + q_T, \\
\frac{\partial C}{\partial t} = \kappa_C \nabla^2 C + q_C,
\]

In the present example, diffusivities are fixed to be \( \kappa_T = \kappa_C = 1 \). Heat and composition sources are given as \( q_T = \frac{2}{r} \) and \( q_C = 1.0 \), respectively. The source terms are given in the initial field data. The procedure of the simulation is the same as for the dynamo benchmark Case 1. However, initial field generation program sph_initial_field is required to build by the following process:

1. Copy source file `const_sph_initial_spectr.f90` to 
   `[CALYPSO_DIR]/src/programs/data_utilities/INITIAL_FIELD`

   `\verb|[sph_initial_field]| INITIAL_FIELD`

2. Build initial field generation program again.
3. Return to the example directory

[work]$ cd [CALYPSO_DIR]/examples/heat_composition_source

After building `sph_initial_field`, the procedure is the same as for the dynamo benchmarks. After the simulation, \(Y_0^0\) component of temperature and composition as a function of radius and time is written in `picked_mode.dat`.

### 8.5 Example of thermal and compositional boundary conditions by external file

Heterogeneous boundary are input using an external file. An example to set thermal and compositional boundary conditions is given in `heterogeneous_temp` directory. As in the heat source example, only the diffusion problem is solved in this example. In file `bc_spectr.btx`, temperature boundary conditions are defined for \(Y_0^0\), \(Y_1^{1s}\), \(Y_1^{1c}\), and \(Y_2^{2c}\) component, and compositional boundary is defined for \(Y_0^0\), \(Y_2^{2s}\), and \(Y_2^{2c}\) components. The radial profile of these spherical harmonics coefficients are written in `picked_mode.dat`. 
## 9 Preprocessing program (*gen_sph_grid*)

This program generates index table and a communication table for parallel spherical harmonics, table of integrals for Coriolis term, and FEM mesh information to generate visualization data (see Figure 4). This program needs control file for input. This program can perform with any number of MPI processes less than the number of subdomains. The output files include the indexing tables.

**Table 2: List of files for *gen_sph_grid***

<table>
<thead>
<tr>
<th>extension</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_sph_grid</td>
<td>Single</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Output</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rlm</td>
<td>Distributed</td>
<td>Output</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtm</td>
<td>Distributed</td>
<td>Output</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtp</td>
<td>Distributed</td>
<td>Output</td>
</tr>
<tr>
<td>radial_info.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
</tbody>
</table>
9.1 Position of radial grid

The preprocessing program sets the radial grid spacing, either by a list in the control file or by setting an equidistant grid or Chebyshev collocation points.

In equidistance grid, radial grids are defined by

\[ r(k) = r_i + (r_o - r_i) \frac{k - k_{ICB}}{N}, \]

where, \( k_{ICB} \) is the grid points number at ICB. The radial grid set from the closest points of minimum radius defined by \([\text{Min\_radius\_ctl}]\) in control file to the closest points of the maximum radius defined by \([\text{Max\_radius\_ctl}]\) in control file, and radial grid number for the innermost points is set to \( k = 1 \).

In Chebyshev collocation points, radial grids in the fluid shell are defined by

\[ r(k) = r_i + \frac{(r_o - r_i)}{2} \left[ \frac{1}{2} - \cos \left( \frac{\pi k - k_{ICB}}{N} \right) \right], \]

For the inner core \((r < r_i)\), grid points is defined by

\[ r(k) = r_i - \frac{(r_o - r_i)}{2} \left[ \frac{1}{2} - \cos \left( \frac{\pi k - k_{ICB}}{N} \right) \right], \]

and, grid points in the external of the shell \((r > r_o)\) is defined by

\[ r(k) = r_o + \frac{(r_o - r_i)}{2} \left[ \frac{1}{2} - \cos \left( \frac{\pi k - k_{CMB}}{N} \right) \right], \]

where, \( k_{CMB} \) is the grid point number at CMB.

9.2 Control file (control_sph_shell)

Control files for Calypso consists of blocks starting and ending with \textit{begin} and \textit{end}, respectively. Entities with more than one components are defined between \textit{begin array} and \textit{end array} flags. The number of components of an array must be defined at \textit{begin array} line. If blocks to be defined in an external file, the external file name is defined by \textit{file} flag.

Control file (control_sph_shell) consists the following items. Detailed description for each item can be checked by clicking "(Detail)" at the end of each item.
• data_files_def
  - num_subdomain_ctl
  - sph_file_prefix

• num_domain_ctl
  - num_radial_domain_ctl
  - num_horizontal_domain_ctl
  - array num_domain_sph_grid
  - array num_domain_legendre
  - array num_domain_spectr

• num_grid_sph
  - truncation_level_ctl
  - ngrid_meridonal_ctl
  - ngrid_zonal_ctl
  - radial_grid_type_ctl
  - num_fluid_grid_ctl
  - fluid_core_size_ctl
  - ICB_to_CMB_ratio_ctl
  - Min_radius_ctl
  - Max_radius_ctl
  - array r_layer
  - array boundaries_ctl

If num_radial_domain_ctl and num_horizontal_domain_ctl are defined, the following arrays num_domain_sph_grid, num_domain_legendre, and num_domain_spectr are not necessary. (see example spherical_shell/with_inner_core)
9.3 Spectrum index data

gen_sph_grid generates indexing table of the spherical transform. To perform spherical harmonics transform with distributed memory computers, data communication table is also included in these files. Calypso needs four indexing data for the spherical transform.

\([\text{sph\_prefix}].[\text{domain#}].rj\) Indexing table for spectrum data \(f(r,l,m)\) to calculate linear terms. In program, spherical harmonics modes \((l,m)\) is indexed by \(j = l(l+1)+m\). The spectrum data are decomposed by spherical harmonics modes \(j\). Data communication table for Legendre transform is included. The data also have the radial index of the ICB and CMB.

\([\text{sph\_prefix}].[\text{domain#}].rlm\) Indexing table for spectrum data \(f(r,l,m)\) for Legendre transform. The spectrum data are decomposed by radial direction \(r\) and spherical harmonics order \(m\). Data communication table to caricurate liner terms is included.

\([\text{sph\_prefix}].[\text{domain#}].rtm\) Indexing table for data \(f(r,\theta,m)\) for Legendre transform. The data are decomposed by radial direction \(r\) and spherical harmonics order \(m\). Data communication table for backward Fourier transform is included.

\([\text{sph\_prefix}].[\text{domain#}].rtp\) Indexing table for data \(f(r,\theta,m)\) for Fourier transform and field data \(f(r,\theta,\phi)\). The data are decomposed by radial direction \(r\) and meridional direction \(\theta\). Data communication table for forward Legendre transform is included.

9.4 Finite element mesh data

Calypso generates field data for visualization with XDMF or VTK format. To generate field data file, the preprocessing program generates FEM mesh data for each subdomain of spherical grid \((r,\theta,\phi)\) under the Cartesian coordinate \((x,y,z)\). The mesh data file is written as GeoFEM (http://geofem.tokyo.rist.or.jp) mesh data format, which consists of each subdomain mesh and communication table among overlapped nodes.

9.5 Radial grid data

The preprocessing program generates radius of each layer in radial_info.dat if radial_grid_type_ctl is set to Chebyshev or equi_distance. This file consists of blocks array \(r\_layer\) and array boundaries_ctl for control file. This data may be useful if you want to modify radial grid spacing by yourself.
### 9.6 How to define spatial resolution and parallelization?

Calypso uses spherical harmonics expansion method and in horizontal discretization and finite difference methods in the radial direction. In the spherical harmonics expansion methods, nonlinear terms are solved in the grid space while time integration and diffusion terms are solved in the spectrum space. We need to set truncation degree $l_{\text{max}}$ of the spherical harmonics and number of grids in the three direction ($N_r, N_\theta, N_\phi$) in the preprocessing program. The following condition is required (or recommended) for $l_{\text{max}}$ and ($N_r, N_\theta, N_\phi$). $l_{\text{max}}$ is defined by `truncation_level_ctl`, and $N_r$ for the fluid shell (outer core) is defined by `num_fluid_grid_ctl`. $N_\theta$ and $N_\phi$ is defined by `ngrid_meridional_ctl` and `ngrid_zonal_ctl`, respectively.

- \( N_\phi = 2N_\theta \).
- \( N_\theta \) must be more than $l_{\text{max}} + 1$, but
- To eliminate aliasing in the spherical transform, \( N_\theta \geq 1.5 (l_{\text{max}} + 1) \) is highly recommended.
- \( N_\phi \) should consists of products among power of 2, power of 3, and power of 5.

Calypso is parallelized 2-dimensionally and direction of the parallelization is changed in the operations in the spherical transform (See Figure 5). Two dimensional parallelization delivers many parallelize configuration. Here is the approach how to find the best configuration:

- Maximum parallelization level in horizontal direction is \( (l_{\text{max}} + 1) /2 \), and $N_r + 1$ is the maximum level in radial direction.
- Decompose number of radial points $N_r + 1$ and truncation degree \( (l_{\text{max}} + 1) /2 \) into prime numbers.
- Decide number of MPI processes from the prime numbers.
- Choose the number of decomposition in the radial and horizontal direction as close as possible.

Here is an example for the case with \( (N_r, l_{\text{max}}) = (89, 95) \). The maximum number of parallelization is \( 90 \times 48 = 4320 \) processes. $N_r + 1$ and \( (l_{\text{max}} + 1) /2 \) can be decomposed into \( 90 = 2 \times 3^2 \times 5 \) and \( 48 = 2^4 \times 3 \). Now, if 160 processes run is intended, \( 160 = 10 \times 16 \) is the closest number of decompositions. Comparing with the prime numbers of the spatial resolution, radial and horizontal decomposition will be 10 and 16, respectively.
Figure 5: Parallelization and data communication in Calypso in the case using 9 (3x3) processors. Data are decomposed in radial and meridional direction for nonlinear term evaluations, decomposed in radial and harmonic order for Legendre transform, and decomposed in spherical harmonics for linear calculations.
10 Simulation program (sph_mhd)

The name of the simulation program is sph_mhd. This program requires control_MHD as a Control file. This program performs with the indexing file for spherical harmonics and Coriolis term integration file generated by the preprocessing program gen_sph_grid. Data files for this program are listed in Table 3. Indexing data for spherical harmonics which starting with [sph_prefix] are obtained by the preprocessing program gen_sph_grid. The boundary condition data file [boundary_data_name] is optionally required if boundary conditions for temperature and composition are not homogenous.
Table 3: List of files for simulation sph.mhd

<table>
<thead>
<tr>
<th>name</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_MHD</td>
<td>Serial</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rlm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtp</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].gfm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[boundary_data_name]</td>
<td>Single</td>
<td>Input</td>
</tr>
<tr>
<td>[rst_prefix].[step#].[domain#].fst</td>
<td>Distributed</td>
<td>Input/Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_s.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_l.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_m.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_lm.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_ave_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_s.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_l.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_m.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_lm.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[gauss_coef_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[picked_sph_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[nusselt_number_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[fld_prefix].[step#].[domain#].[extension]</td>
<td>-</td>
<td>Output</td>
</tr>
<tr>
<td>[section_prefix].[step#].[extension]</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[isosurface_prefix].[step#].[extension]</td>
<td>Single</td>
<td>Output</td>
</tr>
</tbody>
</table>
10.1 Control file

The format of the control file control_MHD is described below. The detail of each block is described in section [A] You can jump to detailed description by clicking ”(Detail)”.

MHD_control (Header of the control file)

- data_files_def (Detail)
  - num_subdomain_ctl [Num_PE] (Detail)
  - num_smp_ctl [Num_Threads] (Detail)
  - sph_file_prefix [sph_prefix] (Detail)
  - boundary_data_file_name [boundary_data_name] (Detail)
  - restart_file_prefix [rst_prefix] (Detail)
  - field_file_prefix [fld_prefix] (Detail)
  - field_file_fmt_ctl [fld_format] (Detail)

- model
  - phys_values_ctl (Detail)
    * array nod_value_ctl [Field] [Viz_flag] [Monitor_flag] (Detail)
  - time_evolution_ctl (Detail)
    * array time_evo_ctl [Field] (Detail)
  - boundary_condition (Detail)
    * array bc_temperature [Group] [Type] [Value] (Detail)
    * array bc_velocity [Group] [Type] [Value] (Detail)
    * array bc_composition [Group] [Type] [Value] (Detail)
    * array bc_magnetic_field [Group] [Type] [Value] (Detail)
  - forces_define (Detail)
* array force_ctl [Force] (Detail)
- dimensionless_ctl (Detail)
* array dimless_ctl [Name] [Value] (Detail)
- coefficients_ctl (Detail)
  * thermal (Detail)
    · array coef_4_thermal_ctl [Name] [Power] (Detail)
    · array coef_4_t_diffuse_ctl [Name] [Power] (Detail)
    · array coef_4_heat_source_ctl [Name] [Power] (Detail)
  * momentum (Detail)
    · array coef_4_velocity_ctl [Name] [Power] (Detail)
    · array coef_4_press_ctl [Name] [Power] (Detail)
    · array coef_4_v_diffuse_ctl [Name] [Power] (Detail)
    · array coef_4_buoyancy_ctl [Name] [Power] (Detail)
    · array coef_4_Coriolis_ctl [Name] [Power] (Detail)
    · array coef_4_Lorentz_ctl [Name] [Power] (Detail)
    · array coef_4_composit_buoyancy_ctl [Name] [Power] (Detail)
  * induction (Detail)
    · array coef_4_magnetic_ctl [Name] [Power] (Detail)
    · array coef_4_m_diffuse_ctl [Name] [Power] (Detail)
    · array coef_4_induction_ctl [Name] [Power] (Detail)
  * composition (Detail)
    · array coef_4_composition_ctl [Name] [Power] (Detail)
    · array coef_4_c_diffuse_ctl [Name] [Power] (Detail)
    · array coef_4_composition_source_ctl [Name] [Power] (Detail)
- temperature_define (Detail)
  * ref_temp_ctl [REFERENCE_TEMP] (Detail)
  * low_temp_ctl (Detail)
    · depth [RADIUS] (Detail)
    · temperature [TEMPERATURE] (Detail)
* high_temp_ctl (Detail)
  · depth [RADIUS] (Detail)
  · temperature [TEMPERATURE] (Detail)

• control
  - time_step_ctl (Detail)
    * elapsed_time_ctl [ELAPSED_TIME] (Detail)
    * i_step_init_ctl [ISTEP_START] (Detail)
    * i_step_finish_ctl [ISTEP_FINISH] (Detail)
    * i_step_check_ctl [ISTEP_MONITOR] (Detail)
    * i_step_rst_ctl [ISTEP_RESTART] (Detail)
    * i_step_field_ctl [ISTEP_FIELD] (Detail)
    * i_step_sectioning_ctl [ISTEP_SECTION] (Detail)
    * i_step_isosurface_ctl [ISTEP_ISOSURFACE] (Detail)
    * dt_ctl [DELTA_TIME] (Detail)
    * time_init_ctl [INITIAL_TIME] (Detail)
  - restart_file_ctl (Detail)
    * rst_ctl [INITIAL_TYPE] (Detail)
  - time_loop_ctl (Detail)
    * scheme_ctl [EVOLUTION_SCHEME] (Detail)
    * coef_imp_v_ctl [COEF_INP_U] (Detail)
    * coef_imp_t_ctl [COEF_INP_T] (Detail)
    * coef_imp_b_ctl [COEF_INP_B] (Detail)
    * coef_imp_c_ctl [COEF_INP_C] (Detail)
    * FFT_library_ctl [FFT_Name] (Detail)
    * Legendre_trans_loop_ctl [Leg_Loop] (Detail)

• sph_monitor_ctl (Detail)
  - volume_average_prefix [vol_ave_prefix] (Detail)
  - volume_pwr_spectr_prefix [vol_pwr_prefix] (Detail)

45
10.2 Spectrum data for restarting

Spectrum data is used for restarting data and generating field data by Data transform programs `sph_snapshot`, `sph_zm_snapshot`, or `sph_dynamobench`. This file is saved for each subdomain (MPI processes), then [step #] and [domain #] are added in the file name. The [step #] is calculated by time step / [ISTEP_RESTART].
10.3 Thermal and compositional boundary condition data file

Thermal and compositional heterogeneity at boundaries are defined by a external file named [boundary_data_name]. In this file, temperature, composition, heat flux, or compositional flux at ICB or CMB can be defined by spherical harmonics coefficients. To use boundary conditions in [boundary_data_name], file name is defined by boundary_data_file_name column in control file, and boundary condition type [type] is set to fixed_file or fixed_flux_file in bc_temperature or bc_composition column. By setting fixed_file or fixed_flux_file in control file, boundary conditions are copied from the file [boundary_data_name].

An example of the boundary condition file is shown in Figure 7. As for the control file, a line starting from ‘#’ or ‘!’ is recognized as a comment line. In [boundary_data_name], boundary condition data is defined as following:

1. Number of total boundary conditions to be defined in this file.
2. Field name to define the first boundary condition
3. Place to define the first boundary condition (ICB or CMB)
4. Number of spherical harmonics modes for each boundary condition
5. Spectrum data for the boundary conditions (degree $l$, order $m$, and harmonics coefficients)
6. After finishing the list of spectrum data return to Step 2 for the next boundary condition

If harmonics coefficients of the boundary conditions are not listed in item 5, 0.0 is automatically applied for the harmonics coefficients of the boundary conditions. So, only non-zero components need to be listed in the boundary condition file.

10.4 Field data for visualization

Field data is used for the visualization processes. Field data are written with XDMF format (http://www.xdmf.org/index.php/Main_Page), merged VTK, or distributed VTK format (http://www.vtk.org/VTK/img/file-formats.pdf). The output data format is defined by fld_format. Visualization applications which we checked are listed in Table 4. Because the field data is written by using Cartesian coordinate $(x, y, z)$ system, coordinate conversion is required to plot vector field in spherical coordinate $(r, \theta, \phi)$ or cylindrical coordinate $(s, \phi, z)$. We will introduce a example of visualization process using ParaView in Section 18.
# number of boundary conditions
  4

# boundary condition data list
#
# Fixed temperature at ICB
temperature
ICB
  3
  0 0 1.0E+00
  1 1 2.0E-01
  2 2 3.0E-01
#
# Fixed heat flux at CMB
heat_flux
CMB
  2
  0 0 -0.9E+0
  1 -1 5.0E-1
#
# Fixed composition flux at ICB
composite_flux
ICB
  2
  0 0 0.0E+00
  2 0 -2.5E-01
#
# Fixed composition at CMB
composition
CMB
  2
  0 0 1.0E+00
  2 -2 5.0E-01

Figure 7: An example of boundary condition file.
Table 4: Checked visualization application

<table>
<thead>
<tr>
<th>Format</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed VTK</td>
<td>ParaView (<a href="http://www.paraview.org">http://www.paraview.org</a>)</td>
</tr>
<tr>
<td>Merged VTK</td>
<td>ParaView, VisIt (<a href="https://wci.llnl.gov/codes/visit/">https://wci.llnl.gov/codes/visit/</a>) Mayavi (<a href="http://mayavi.sourceforge.net/">http://mayavi.sourceforge.net/</a>)</td>
</tr>
<tr>
<td>XDMF</td>
<td>ParaView, VisIt</td>
</tr>
</tbody>
</table>

10.4.1 Distributed VTK data

Distributed VTK data have the following advantage and disadvantages to use:

- **Advantage**
  - Faster output
  - No external library is required

- **Disadvantage**
  - Many data files are generated
  - Total data file size is large
  - Only ParaView supports this format

Distributed VTK data consist files listed in Table 5. For ParaView, all subdomain data is read by choosing [fld_prefix].[step#].pvtk in file menu.

Table 5: List of written files for distributed VTK format

<table>
<thead>
<tr>
<th>name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[fld_prefix].[step#].[domain#].vtk</td>
<td>VTK data for each subdomain</td>
</tr>
<tr>
<td>[fld_prefix].[step#].pvtk</td>
<td>Subdomain file list for Paraview</td>
</tr>
</tbody>
</table>

10.4.2 Merged VTK data

Merged VTK data have the following advantage and disadvantages to use:
• Advantage
  – Merged field data is generated
  – No external library is required
  – Many applications support VTK format

• Disadvantage
  – Very slow to output
  – Total data file size is large

Merged VTK data generate files listed in Table 6.

Table 6: List of written files for merged VTK format

<table>
<thead>
<tr>
<th>name</th>
<th>Merged VTK data</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{fld_prefix}]).[step#].\text{vtk}</td>
<td></td>
</tr>
</tbody>
</table>

10.4.3 Merged XDMF data

Merged XDMF data have the following advantage and disadvantages to use:

• Advantage
  – Fastest output
  – Merged field data is generated
  – File size is smaller than the VTK formats

• Disadvantage
  – Parallel HDF5 library should be required to use

Merged XDMF data generate files listed in Table 7. For ParaView, all subdomain data is read by choosing \([\text{fld\_prefix}]\).\text{solution.xdmf} in file menu.
### 10.5 Cross section data (Parallel Surfacing module)

Calypso can output cross section data for visualization with finer time increment than the whole domain data. The cross section data consist of triangle patches with VTK format, then data can be visualized by Paraview like as the whole field data. This cross sectioning module can output arbitrary quadrature surface, but plane, sphere, and cylindrical section would be useful for the geodynamo simulations.

To output cross sectioning, increment of the surface output data should be defined by `i_step_sectioning_ctl` in `time_step_ctl` block. And, array block `cross_section_ctl` in `visual_control` section is required to define cross sections. Each `cross_section_ctl` block defines one cross section. Each cross section can also define by an external file by specifying external file name with `file label`. The sections shown in Table 8 are supported in the sectioning module. These surfaces are defined in the Cartesian coordinate. The easiest approach is using sections defined by

<table>
<thead>
<tr>
<th>Surface type</th>
<th>equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrature surface</td>
<td>( ax^2 + by^2 + cz^2 + dyz + ezx + fxy + gx + hy + jz + k = 0 )</td>
</tr>
<tr>
<td>Plane surface</td>
<td>( a(x - x_0) + b(y - y_0) + c(z - z_0) = 0 )</td>
</tr>
<tr>
<td>Sphere</td>
<td>( (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = r^2 )</td>
</tr>
<tr>
<td>Ellipsoid</td>
<td>( \left( \frac{x - x_0}{a} \right)^2 + \left( \frac{y - y_0}{b} \right)^2 + \left( \frac{z - z_0}{c} \right)^2 = 1 )</td>
</tr>
</tbody>
</table>

A plane surface is defined by a normal vector \((a, b, c)\) and one point including the surface \((x_0, y_0, z_0)\) in arrays `normal_vector` and `center_position`, respectively.

A sphere surface is defined by the position of the center \((x_0, y_0, z_0)\) and radius \(r\) in array `center_position` and `radius`, respectively.
An Ellipsoid surface is defined the position of the center \((x_0, y_0, z_0)\) and length of the each axis \((a, b, c)\) in arrays \texttt{center\_position} and \texttt{axial\_length}, respectively. If one component of the \texttt{axial\_length} is set to 0, surfacing module generate a Ellipsoidal tube along with the axis where \texttt{axial\_length} is set to 0.

Area for visualization can be defined by array \texttt{chosen\_ele\_grp\_ctl} by choosing \texttt{outer\_core}, \texttt{inner\_core}, and \texttt{all}. Fields to display is defined in array \texttt{output\_field}. In array \texttt{output\_field}, field type in Table 9 needs to defined. The same field can be defined more than once in array \texttt{output\_field} to output vector field in Cartesian coordinate and radial component, for example.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Field type</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>scalar field</td>
</tr>
<tr>
<td>vector</td>
<td>Cartesian vector field</td>
</tr>
<tr>
<td>(x)</td>
<td>(x)-component</td>
</tr>
<tr>
<td>(y)</td>
<td>(y)-component</td>
</tr>
<tr>
<td>(z)</td>
<td>(z)-component</td>
</tr>
<tr>
<td>radial</td>
<td>radial ((r-)) component</td>
</tr>
<tr>
<td>(\theta)</td>
<td>(\theta)-component</td>
</tr>
<tr>
<td>(\phi)</td>
<td>(\phi)-component</td>
</tr>
<tr>
<td>cylinder_r</td>
<td>cylindrical radial ((s-)) component</td>
</tr>
<tr>
<td>magnitude</td>
<td>magnitude of vector</td>
</tr>
</tbody>
</table>

### 10.5.1 Control file

The format of the control file or block for cross sections is described below. The detail of each block is described in section \texttt{A cross\_section\_ctl} block can be read from an external file. To define the external file name, as file \texttt{cross\_section\_ctl \{file name\}} in \texttt{control\_MHD} or \texttt{control\_snapshot}. You can jump to detailed description by clicking ”(Detail)”.

\texttt{cross\_section\_ctl} (Header of the control file)

- \texttt{section\_file\_prefix \{section\_prefix\}}
- \texttt{surface\_define}
- section_method [METHOD] (Detail)
- array coefs_ctl [TERM] [COEFFICIENT] (Detail)
- radius [SIZE] (Detail)
- array normal_vector [DIRECTION] [COMPONENT] (Detail)
- array axial_length [DIRECTION] [COMPONENT] (Detail)
- array center_position [DIRECTION] [COMPONENT] (Detail)
- array section_area_ctl [AREA_NAME] (Detail)

• output_field_define (Detail)
  - array output_field [FIELD] [COMPONENT] (Detail)

10.6 Isosurface data

Calypso can also output isosurface data for visualization. Generally, data size of the isosurface is much larger than the sectioning data. The isosurface data is also written as a unstructured grid data with VTK format. The isosurface also consists of triangle patches.

To output cross sectioning, increment of the surface output data should be defined by i_step_isosurface_ctl in time_step_ctl block. And, array block isosurface_ctl in visual_control section is required to define cross sections. Each isosurface_ctl block defines one cross section. Each cross section can also define by an external file by specifying external file name with file label.

10.6.1 Control file

The format of the control file or block for isosurfaces is described below. The detail of each block is described in section A. isosurface_ctl block can be read from an external file. To define the external file name, as file isosurface_ctl [file name] in control_MHD or control_snapshot. You can jump to detailed description by clicking "(Detail)".

isosurface_ctl (Header of the control file)

• isosurface_file_prefix [file_prefix] (Detail)
• isosurf_define (Detail)
  - isosurf_field [FIELD] (Detail)
- isosurf_component [COMPONENT] (Detail)
- isosurf_value [VALUE] (Detail)
- array isosurf_area_ctl [AREA_NAME] (Detail)

- field_on_isosurf (Detail)
  - result_type [TYPE] (Detail)
  - result_value [VALUE] (Detail)
  - array output_field [FIELD] [COMPONENT] (Detail)

10.7 Mean square amplitude data

This program outputs mean square amplitude of the fields which is marked as Monitor_ON over the fluid shell at every [increment_monitor] steps. The data is written in the file [vol_pwr_prefix]_s.dat or sph_pwr_volume_s.dat if [vol_pwr_prefix] is not defined in the control file. For vector fields, for the velocity $u$ and magnetic field $B$, the kinetic energy $1/2u^2$ and magnetic energy $1/2B^2$ are calculated instead of mean square amplitude. Labels on the first lines indicate following data. The data file have the following headers in the first 7 lines, and headers of the data and data are stored in the following lines. The header in the first 7 lines is the following. If these mean square amplitude data files exist before starting the simulation, programs append results at the end of files without checking constancy of the number of data and order of the field. If you change the configuration of data output structure, please move the existed data files to another directory before starting the programs.

line 2: Number of radial grid and truncation level
line 4: radial layer ID for ICB and CMB
line 6: Number of field of data, total number of components
line 7: Number of components for each field

Labels for data indicates as

t_step Time step number
time Time
K_ene.pol Amplitude of poloidal kinetic energy
K_enetor Amplitude of toroidal kinetic energy
K_enet Amplitude of total kinetic energy
M_enepol Amplitude of poloidal magnetic energy
M_enetor Amplitude of toroidal magnetic energy
M_ene Amplitude of total magnetic energy

[Field]_pol Mean square amplitude of poloidal component of [Field]
[Field]_tor Mean square amplitude of toroidal component of [Field]
[Field] Mean square amplitude of [Field]

10.7.1 Volume average data

Volume average data are written by defining volume_average_prefix in control file. Volume average data are written in [vol_ave_prefix].dat with same format as RMS amplitude data. If you need the sphere average data for specific radial point, you can use picked spectrum data for \( l = m = 0 \) at specific radius.

10.7.2 Volume spectrum data

Volume spectrum data are written by defining volume_pwr_spectr_prefix in control file. By defining volume_pwr_spectr_prefix, following spectrum data averaged over the fluid shell is written. Data format is the same as the volume mean square data, but degree \( l \), order \( m \), or meridional wave number \( l - m \) is added in the list of data.

\([\text{vol_pwr_prefix}\_l].\text{dat}\) Volume average of mean square amplitude of the fields as a function of spherical harmonic degree \( l \). For scalar field, the spectrum is

\[
fsq(l) = \frac{1}{V} \sum_{m=-l}^{m=l} \int (f^m_l)^2 dV.
\]

For vector field, spectrum for the poloidal and toroidal components are written by

\[
B_{Sq}(l) = \frac{1}{V} \sum_{m=-l}^{m=l} \int (B^{m}_{S\ell})^2 dV,
\]

\[
B_{Tq}(l) = \frac{1}{V} \sum_{m=-l}^{m=l} \int (B^{m}_{T\ell})^2 dV.
\]
If the vector field $F$ is not solenoidal (i.e. $\nabla \cdot F \neq 0$), the poloidal component of mean square data are included mean square field of the potential components as

$$F_{S\text{sq}}(l) = \frac{1}{V} \sum_{m=-l}^{m=l} \int \left[ (B_{Sl}^m)^2 + (-\nabla \phi_{Fl}^m)^2 \right] dV.$$  

[vol_pwr_prefix]_m.dat Volume average of mean square amplitude of the fields as a function of spherical harmonic order $m$. The zonal wave number is referred in this spectrum data. For scalar field, the spectrum is

$$f_{S\text{sq}}(m) = \frac{1}{V} \sum_{l=0}^{l=m} \int \left[ (f_l^m)^2 + (f_{l-m}^m)^2 \right] dV.$$  

For vector field, spectrum for the poloidal and toroidal components are written by

$$B_{S\text{sq}}(m) = \frac{1}{V} \sum_{l=0}^{l=m} \int \left[ (B_{Sl}^m)^2 + (B_{Sl}^{-m})^2 \right] dV,$$

$$B_{T\text{sq}}(m) = \frac{1}{V} \sum_{l=0}^{l=m} \int \left[ (B_{Tl}^m)^2 + (B_{Tl}^{-m})^2 \right] dV.$$  

[vol_pwr_prefix]_lm.dat Volume average of mean square amplitude of the fields as a function of spherical harmonic order $n = l - m$. The wave number in the latitude direction is referred in this spectrum data. For scalar field, the spectrum is

$$f_{S\text{sq}}(n) = \frac{1}{V} \sum_{l=n}^{l=n-l} \int \left[ (f_{l-n}^l)^2 + (f_{l+n}^{-l})^2 \right] dV.$$  

For vector field, spectrum for the poloidal and toroidal components are written by

$$B_{S\text{sq}}(n) = \frac{1}{V} \sum_{l=n}^{l=n-l} \int \left[ (B_{Sl}^{l-n})^2 + (B_{Sl}^{-l+n})^2 \right] dV,$$

$$B_{T\text{sq}}(n) = \frac{1}{V} \sum_{l=n}^{l=n-l} \int \left[ (B_{Tl}^{l-n})^2 + (B_{Tl}^{-l+n})^2 \right] dV.$$
10.7.3 layered spectrum data

Spectrum data for the each radial position are written by defining `layered_pwr_spectr_prefix` in control file. By defining `layered_pwr_spectr_prefix`, following spectrum data averaged over the fluid shell is written. Data format is the same as the volume spectrum data, but radial grid point and radius of the layer is added in the list. The following files are generated. The radial points for output is listed in the array `spectr_layer_ctl`. If `spectr_layer_ctl` is not defined, mean square data at all radial levels will be written. See example of [dynamo benchmark case 2](#).

- \([\text{layer.pwr.prefix}]_s.dat\) surface average of mean square amplitude of the fields.
- \([\text{layer.pwr.prefix}]_l.dat\) surface average of mean square amplitude of the fields as a function of spherical harmonic degree \(l\) and radial grid id \(k\). For scalar field, the spectrum is

\[
 f_{sq}(k, l) = \frac{1}{S} \sum_{m=-l}^{m=l} \int (f_l^m)^2 dS.
\]

For vector field, spectrum for the poloidal and toroidal components are written by

\[
 B_{Sq}(k, l) = \frac{1}{S} \sum_{m=-l}^{m=l} \int (B_{Sl}^m)^2 dS,
\]

\[
 B_{Tq}(k, l) = \frac{1}{S} \sum_{m=-l}^{m=l} \int (B_{Tl}^m)^2 dS.
\]

- \([\text{layer.pwr.prefix}]_m.dat\) surface average of mean square amplitude of the fields as a function of spherical harmonic order \(m\) and radial grid id \(k\). The zonal wave number is referred in this spectrum data. For scalar field, the spectrum is

\[
 f_{sq}(k, m) = \frac{1}{S} \sum_{l=-L}^{l=L} \int \left[ (f_l^m)^2 + (f_{-l}^{-m})^2 \right] dS.
\]

For vector field, spectrum for the poloidal and toroidal components are written by

\[
 B_{Sq}(k, m) = \frac{1}{S} \sum_{l=-L}^{l=L} \int \left[ (B_{Sl}^m)^2 + (B_{Sl}^{-m})^2 \right] dS,
\]

\[
 B_{Tq}(k, m) = \frac{1}{S} \sum_{l=-L}^{l=L} \int \left[ (B_{Tl}^m)^2 + (B_{Tl}^{-m})^2 \right] dS.
\]
Surface average of mean square amplitude of the fields as a function of spherical harmonic order \( n = l - m \) and radial grid id \( k \). The wave number in the latitude direction is referred in this spectrum data. For scalar field, the spectrum is

\[
fsq(k, n) = \frac{1}{S} \sum_{l=n}^{l=L} \int \left[ (f_l^{l-n})^2 + (f_l^{-l+n})^2 \right] dS.
\]

For vector field, spectrum for the poloidal and toroidal components are written by

\[
BSsq(k, n) = \frac{1}{S} \sum_{l=n}^{l=L} \int \left[ (B_{Sl}^{l-n})^2 + (B_{St}^{l+n})^2 \right] dS,
\]

\[
BTsq(k, n) = \frac{1}{S} \sum_{l=n}^{l=L} \int \left[ (B_{Ti}^{l-n})^2 + (B_{Tt}^{l+n})^2 \right] dS.
\]

10.8 Gauss coefficient data [gauss_coef_prefix].dat

This program output selected Gauss coefficients of the magnetic field. Gauss coefficients is evaluated for radius defined by \([\text{gauss_coef_radius}]\) every \([\text{increment_monitor}]\) steps. Gauss coefficients are evaluated by using poloidal magnetic field at CMB \(B_{Sl}^m(r_o)\) and radius defined by \([\text{gauss_coef_radius}]\) \( r_e \) as

\[
g^m_l = \frac{l}{r_e^2} \left( \frac{r_o}{r_e} \right)^l B_{Sl}^m(r_o),
\]

\[
h^m_l = \frac{l}{r_e^2} \left( \frac{r_o}{r_e} \right)^l B_{St}^m(r_o).
\]

The data file has the following headers in the first three lines,

line 2: Number of saved Gauss coefficients and reference radius.

line 3: Labels of Gauss coefficients data.

The data consists of time step, time, and Gauss coefficients for each step in one line. If the Gauss coefficients data file exist before starting the simulation, programs append Gauss coefficients at the end of files without checking constancy of the number of data and order of the field. If you change the configuration of data output structure, please move the old Gauss coefficients file to another directory before starting the programs.
10.9 **Spectrum monitor data** [picked_sph_prefix].dat

This program outputs spherical harmonics coefficients at specified spherical harmonics modes and radial points in single text file. Spectrum data marked [Monitor_On] are written in our line for each spherical harmonics mode and radial point every [increment_monitor] steps. If the spectrum monitor data file exist before starting the simulation, programs append spectrum data at the end of files without checking constancy of the number of data and order of the field. If you change the configuration of data output structure, please move the old spectrum monitor file to another directory before starting the programs.

If a vector field $F$ is not a solenoidal field, $F$ is described by the spherical harmonics coefficients of the poloidal $F_{Sl}^m$, toroidal $F_{Tl}^m$, and potential $\varphi_l^m$ components as

$$
F(r, \theta, \phi) = -\frac{1}{r^2} \frac{\partial \varphi_0^0}{\partial r} \hat{r} + \sum_{l=1}^{L} \sum_{m=-l}^{l} \left[ \nabla \times \nabla \times (F_{Sl}^m \hat{r}) + \nabla \times (F_{Tl}^m) - \nabla (\varphi_l^m Y^m_l) \right].
$$

In Calypso, the following coefficients are written for the non-solenoidal vector.

- **[field_name]_pol**:
  
  $$
  F_{Sl}^m - \frac{r^2}{l(l+1)} \frac{\partial \varphi_l^m}{\partial r} \quad \text{for} \quad (l \neq 0) \\
  -r^2 \frac{\partial \varphi_0^0}{\partial r} \quad \text{for} \quad (l = 0)
  $$

- **[field_name]_dpdr**:
  
  $$
  \frac{\partial F_{Sl}^m}{\partial r} - \varphi_l^m \quad \text{for} \quad (l \neq 0) \\
  0 \quad \text{for} \quad (l = 0)
  $$

- **[field_name]_tor**:
  
  $$
  F_{Tl}^m
  $$

10.10 **Nusselt number data** [nusselt_number_prefix].dat

**CAUTION**: Nusselt number is not evaluated if heat source is exist. The Nusselt number $Nu$ at CMB and ICB is written for each step in one line. The Nusselt number is evaluated by

$$
Nu = \frac{< \partial T/\partial r >}{\partial T_{diff}/\partial r},
$$

where, $< \partial T/\partial r >$ and $T_{diff}$ are the horizontal average of the temperature gradient at ICB and CMB and diffusive temperature profile, respectively. $T_{diff}$ is evaluated without
heat source, as

\[ T_{diff} = \frac{r_o T_o - r_i T_i}{r_o - r_i} + \frac{r_o r_i (T_i - T_o)}{r_o - r_i} \frac{1}{r}. \]

This diffusive temperature profile is for the case without heat source in the fluid. If simulation is performed including the heat source, this data file does not written. If the Nusselt number data file exist before starting the simulation, programs append spectrum data at the end of files without checking constancy. If you change the configuration of data output structure, please move the old spectrum monitor file to another directory before starting the programs.
11  Data transform program
(sph_snapshot and sph_zm_snapshot)

Simulation program outputs spectrum data as a whole field data. This program generates field data from spectrum data for visualization. This program also can pick Gauss coefficients, mean square data over sphere or each surface from spectrum data as the simulation program.

This program requires control file control_snapshot. File format of the control file is same as the control field for simulation control_MHD.

The same files as the simulation program are read in this program, and field data are generated from the snapshots of spectrum data. The monitoring data for snapshots can also be generated. [step #] is added in the file name, and the [step #] is calculated by time step/[ISTEP_FIELD].

We recommend to output cross section data at $y = 0$ by using sectioning module (see 10.5) for zonal mean snapshot program sph_zm_snapshot to reduce data size.
Table 10: List of files for simulation sph_snap and sph_zm_snap

<table>
<thead>
<tr>
<th>name</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_snapshot</td>
<td>Serial</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rlm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtp</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].gfm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[boundary_data_name]</td>
<td>Single</td>
<td>Input</td>
</tr>
<tr>
<td>[rst_prefix].[step#].[domain#].fst</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[vol_pwr_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_l.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_m.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_lm.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[vol_ave_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_l.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_m.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_lm.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[gauss_coef_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[picked_sph_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[nusselt_number_prefix].dat</td>
<td>Single</td>
<td>Output</td>
</tr>
<tr>
<td>[fld_prefix].[step#].[domain#].[extension]</td>
<td>-</td>
<td>Output</td>
</tr>
</tbody>
</table>
12 Initial field generation program
(sph_initial_field)

Figure 9: Data flow for initial field generation program.

The initial fields for dynamo benchmark can set in the simulation program by setting [INITIAL_TYPE] flag. This program is used to generate initial field by user. The heat source $q_T$ and light element source $q_C$ are also defined by this program because $q_T$ and $q_C$ are defined as scalar fields. The Fortran source file to define initial field const_sph_initial_spectr.f90 is saved in src/programs/data_utilities/INITIAL_FIELD/ directory, and please compile again after modifying this module. This program also needs the files listed in Table 11. This program generates the spectrum

Table 11: List of files for simulation sph_initial_field

<table>
<thead>
<tr>
<th>name</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_MHD</td>
<td>Serial</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rlm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtp</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[rst_prefix].0.[domain#].fst</td>
<td>Distributed</td>
<td>Input/Output</td>
</tr>
</tbody>
</table>

data files [rst_prefix].0.[domain#].fst. To use generated initial data file,
12.1 Definition of the initial field

To construct Initial field data, you need to edit the source code `const_sph_initial_spectr.f90` in the `src/programs/data_utilities/INITIAL_FIELD/` directory. The module `const_sph_initial_spectr` consists of the following subroutines:

- **sph_initial_spectrum**: Top subroutine to construct initial field.
- **set_initial_velocity**: Routine to construct initial velocity.
- **set_initial_temperature**: Routine to construct initial temperature.
- **set_initial_composition**: Routine to construct initial composition.
- **set_initial_magne_sph**: Routine to construct initial magnetic field.
- **set_initial_heat_source_sph**: Routine to construct heat source.
- **set_initial_light_source_sph**: Routine to construct composition source.

The construction routine for each field are called from the top routine `const_sph_initial_spectr.f90`. If lines to call subroutines are commented out, corresponding initial fields are set to 0. In addition, the initial fields to be constructed need to be defined by `nod_value_ctl` array in the `control_MHD`.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Scalar</th>
<th>Poloidal</th>
<th>Toroidal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>-</td>
<td>ipol%i_velo</td>
<td>itor%i_velo</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>-</td>
<td>ipol%i_magne</td>
<td>itor%i_magne</td>
</tr>
<tr>
<td>Current density</td>
<td>-</td>
<td>ipol%i_current</td>
<td>itor%i_current</td>
</tr>
<tr>
<td>Temperature</td>
<td>ipol%i_temp</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composition</td>
<td>ipol%i_light</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat source</td>
<td>ipol%i_heat_source</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Composition source</td>
<td>ipol%i_light_source</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 12: Field name and corresponding field id in Calypso
Initial fields need to be defined by the spherical harmonics coefficients at each radial points as array $d_{rj}(i, i_{\text{field}})$, where $i$ and $i_{\text{field}}$ are the local address of the spectrum data and field id, respectively. The address of the fields are listed in Table 12.

In Calypso, local data address for each MPI process is used for the spectrum data address $i$. To find the local address $i$, two functions are required. First, $j = \text{find\_local\_sph\_mode\_address}(l, m)$ returns the local spherical harmonics address $j$ from a spherical harmonics mode $Y_{l}^{m}$. If process does not have the data for $Y_{l}^{m}$, $j$ is set to 0. Second, $i = \text{local\_sph\_data\_address}(k, j)$ returns the local data address $i$ from radial grid number $k$ and local spherical harmonics id $j$. For do loops in the radial direction, the total number of radial grid points, radial address for ICB, and radial address for CMB are defined as $nidx_{rj}(1), nlayer_{ICB}$, and $nlayer_{CMB}$, respectively. The radius for the $k$-th grid points can be obtained by $r = \text{radius\_1d\_rj\_r}(k)$. The subroutines to define initial temperature for the dynamo benchmark Case 1 is shown below as an example.

After updating the source code, the program $\text{sph\_initial\_field}$ needs to be updated. To update the program, move to the work directory $[\text{CALYPSO\_HOME}]$/work and run make command as

```
% cd \\verb|[CALYPSO\_HOME]/work|
% make
```

Then, the program $\text{sph\_initial\_field}$ and $\text{sph\_add\_initial\_field}$ are updated.

```fortran
! subroutine set_initial_temperature

use m_sph_spectr_data

integer ( kind = kint ) :: inod, k, jj
real (kind = kreal ) :: pi, rr, xr, shell
real (kind = kreal ), parameter :: A_temp = 0.1d0

!$omp parallel do
do inod = 1, nnod_rj
   d_rj(inod, ipol%i_temp) = zero
end do
$omp end parallel do
```

65
pi = four * atan(one)
shell = r_CMB - r_ICB

search address for (l = m = 0)
jj = find_local_sph_mode_address(0, 0)

set reference temperature if (l = m = 0) mode is there
if (jj .gt. 0) then
  do k = 1, nlayer_ICB-1
    inod = local_sph_data_address(k,jj)
d_rj(inod,ipol%i_temp) = 1.0d0
  end do
  do k = nlayer_ICB, nlayer_CMB
    inod = local_sph_data_address(k,jj)
d_rj(inod,ipol%i_temp) = (ar_1d_rj(k,1) * 20.d0/13.0d0 &
                           - 1.0d0 ) * 7.0d0 / 13.0d0
  end do
end if

Find local address for (l,m) = (4,4)
jj = find_local_sph_mode_address(4, 4)
jj = find_local_sph_mode_address(5, 5)

If data for (l,m) = (4,4) is there, set initial temperature
if (jj .gt. 0) then
  Set initial field from ICB to CMB
  do k = nlayer_ICB, nlayer_CMB
    ! Set radius data
    rr = radius_1d_rj_r(k)
    ! Set 1d address to substitute at (Nr, j)
    inod = local_sph_data_address(k,jj)
    ! set initial temperature
    xr = two * rr - one * (r_CMB+r_ICB) / shell
d_rj(inod,ipol%i_temp) = (one-three*xr**2+three*xr**4-xr**6) &
& * A_temp * three / (sqrt(two*pi))
        end do
      end if
!
! Center
  if(inod_rj_center .gt. 0) then
    jj = find_local_sph_mode_address(0, 0)
    inod = local_sph_data_address(1, jj)
    d_rj(inod_rj_center, ipol%i_temp) = d_rj(inod, ipol%i_temp)
  end if
!
end subroutine set_initial_temperature
!

13 Initial field modification program  
(sph_add_initial_field)

Figure 10: Data flow for initial field modification program.

Caution: This program overwrites existing initial field data. Please run it after taking a backup.

This program modifies or adds new data to an initial field file. It could be used to start a new geodynamo simulation by adding seed magnetic field or source terms to
a non-magnetic convection simulation. The initial fields to be added are also defined in `const_sph_initial_spectr.f90`. These files are located in the `data_utilities/INITIAL_FIELD` directory. This program also needs the files listed in Table 13. This program generates the

<table>
<thead>
<tr>
<th>name</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>control_MHD</code></td>
<td>Serial</td>
<td>Input</td>
</tr>
<tr>
<td><code>[sph_prefix].[domain#].rj</code></td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td><code>[sph_prefix].[domain#].rlm</code></td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td><code>[sph_prefix].[domain#].rtm</code></td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td><code>[sph_prefix].[domain#].rtp</code></td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td><code>[rst_prefix].[step #].[domain#].fst</code></td>
<td>Distributed</td>
<td>Input/Output</td>
</tr>
</tbody>
</table>

spectrum data files `[rst_prefix].[step#].[domain#].fst`. To use generated initial data file, set `ISTEP_START` and `ISTEP_RESTART` to be appropriate time step and increment, respectively. To read the original initial field data, `INITIAL_TYPE` is set to be `start_from_rst_file` in `control_MHD`. In other words, the `step #` in the file name, `ISTEP_START`, and `ISTEP_RESTART` in the control file should be the consistent.

This program also uses the module file `const_sph_initial_spectr.f90` to define the initial field. The initial fields are defined as following the previous section 12.1. After updating the source code, the program `sph_initial_field` needs to be updated. After modifying `const_sph_initial_spectr.f90`, the program is build by make command in the work directory `CALYPSO_HOME/work`.

14 Check program for dynamo benchmark
(sph_dynamobench)

This program is only used to check solution for dynamo benchmark by Christensen et. al. The following files are used for this program.
Table 14: List of files for dynamo benchmark check sph_dynamobench

<table>
<thead>
<tr>
<th>name</th>
<th>Parallelization</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_snapshot</td>
<td>Serial</td>
<td>I/O</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rlm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtm</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rtp</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[rst_prefix].[step#].[domain#].fst</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>dynamobench.dat</td>
<td>Single</td>
<td>Output</td>
</tr>
</tbody>
</table>

14.1 Dynamo benchmark data dynamobench.dat

In benchmark test by Christensen et. al., both global values and local values are checked. As global results, Kinetic energy \( \frac{1}{V} \int \frac{1}{2} u^2 dV \) in the fluid shell, magnetic energy in the fluid shell \( \frac{1}{V} \frac{1}{EPm} \int \frac{1}{2} B^2 dV \) (for case 1 and 2), and magnetic energy in the solid inner sphere \( \frac{1}{V_i} \frac{1}{EPm} \int \frac{1}{2} B^2 dV_i \) (for case 2 only). Benchmark also requests By increasing number of grid point at mid-depth of the fluid shell in the equatorial plane by nphi_mid_eq_ctl, program can find accurate solution for the point where \( u_r = 0 \) and \( \partial u_r / \partial \phi > 0 \). Angular frequency of the field pattern with respect to the \( \phi \) direction is also required. The benchmark test also requires temperature and \( \theta \) component of velocity.

In the text file dynamobench.dat, the following data are written in one line for every [i_step_rst_ctl] step.

- **t_step**: Time step number
- **time**: Time
- **KE.pol**: Poloidal kinetic energy
- **KE_tor**: Toroidal kinetic energy
- **KE_total**: Total kinetic energy
- **ME.pol**: Poloidal magnetic energy (Case 1 and 2)
- **ME_tor**: Toroidal magnetic energy (Case 1 and 2)
**ME_total:** Total magnetic energy (Case 1 and 2)

**ME_pol_ic:** Poloidal magnetic energy in inner core (Case 2)

**ME_tor_icore:** Toroidal magnetic energy in inner core (Case 2)

**ME_total_icore:** Total magnetic energy in inner core (Case 2)

**omega_ic_z:** Angular velocity of inner core rotation (Case 2)

**MAG_torque_ic_z:** Magnetic torque integrated over the inner core (Case 2)

**phi_1...4:** Longitude where $u_r = 0$ and $\partial u_r / \partial \phi > 0$ at mid-depth in equatorial plane.

**omega_vp44:** Drift frequency evaluated by $V^4_S$ component

**omega_vt54:** Drift frequency evaluated by $V^4_T$ component

**B_theta:** $\Theta$ component of magnetic field at requested point.

**v_phi:** $\phi$ component of velocity at requested point.

**temp:** Temperature at requested point.

<table>
<thead>
<tr>
<th>t_step</th>
<th>time</th>
<th>KE_pol</th>
<th>KE_tor</th>
<th>KE_total</th>
<th>ME_pol</th>
<th>ME_tor</th>
<th>ME_total</th>
<th>omega_ic</th>
<th>MAG_torque_ic_z</th>
<th>phi_1</th>
<th>phi_2</th>
<th>phi_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000</td>
<td>2.001</td>
<td>9.999999999998981E-001</td>
<td>1.534059732073072E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td>2.001</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td>3.965499203357688E+000</td>
<td>2.405694011955049E+000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

...
15 Data assemble program \texttt{(assemble\_sph)}

Calypso uses distributed data files for simulations. This program is to generate new spectrum data for restarting with different spatial resolution or parallel configuration. This program organizes new spectral data by using specter indexing data using different domain decomposition. The following files used for data IO. If radial resolution is changed from the original data, the program makes new spectrum data by linear interpolation. If new data have smaller or larger truncation degree, the program fills zero to the new spectrum data or truncates the data to fit the new spatial resolution, respectively. This program can perform with any number of MPI processes, but we recommend to run the program with one process or the same number of processes as the number of subdomains for the target configuration which is defined by \texttt{num\_new\_domain\_ctl}. Data files for the program are shown in Table 15. The time and number of time step can also be changed by this program. The new time and time step are defined by the parameters in \texttt{new\_time\_step\_ctl} block. The step number of the restart data will be $\texttt{i\_step\_init\_ctl/i\_step\_rst\_ctl}$ in \texttt{new\_time\_step\_ctl}. If \texttt{new\_time\_step\_ctl} block is not defined, time and time step informations are carried from the original restart data.

15.1 Format of control file

Control file consists the following groups.

\begin{verbatim}
assemble\_control
  \bullet data\_files\_def(Detail)
\end{verbatim}
Table 15: List of files for assemble_sph

<table>
<thead>
<tr>
<th></th>
<th>Distributed?</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>control_sph_assemble</td>
<td>Serial</td>
<td></td>
</tr>
<tr>
<td>[sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[new_sph_prefix].[domain#].rj</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[rst_prefix].[step#].[domain#].fst</td>
<td>Distributed</td>
<td>Input</td>
</tr>
<tr>
<td>[new_rst_prefix].[step#].[domain#].fst</td>
<td>Distributed</td>
<td>Output</td>
</tr>
</tbody>
</table>

- num_subdomain_ctl [Num_PE] (Detail)
- sph_file_prefix [sph_prefix] (Detail)
- restart_file_prefix [rst_prefix] (Detail)

- new_data_files_def (Detail)
  - num_new_domain_ctl [new_num_domain] (Detail)
  - new_sph_mode_prefix [new_sph_prefix] (Detail)
  - new_restart_prefix [new_rst_prefix] (Detail)
  - delete_original_data_flag [YES or NO] (Detail)

- control
  - time_step_ctl (Detail)
    * i_step_init_ctl [integer] (Detail)
    * i_step_finish_ctl [integer] (Detail)
    * i_step_rst_ctl [integer] (Detail)
  - new_time_step_ctl (Detail)
    * i_step_init_ctl [integer] (Detail)
    * i_step_rst_ctl [integer] (Detail)
    * time_init_ctl [INITIAL_TIME] (Detail)

- newrst_magne_ctl (Detail)
  - magnetic_field_ratio_ctl [ratio] (Detail)
16 Module dependency program (module_dependency)

This program is only used to generate Makefile in work directory. Most of case, Fortran 90 modules have to compiled prior to be referred by another fortran90 routines. This program is generates dependency lists in Makefile. To use this program, the following limitation is required.

- One source code has to consist of one module.
- The module name should be the same as the file name.

17 Time averaging programs

These small programs are used to evaluate time average and standard deviation of the time evolution data.

17.1 Averaging for mean square and power spectrum
(t_ave_sph_mean_square)

This program generate time average and standard deviation of power spectrum data. The program processes one of data files listed in Table 16. The number for the first and second interactive input is also listed in Table 16. For the third input, the file name excluding .dat is required. Start and end time is also required in the last input. If data is end before the end time, the program will finish at the end of file. t_ave and t_sigma are added at the beginning of the input file name for the time average and standard deviation data file, respectively.

17.2 Averaging for picked harmonics mode data
(t_ave_picked_sph_coefs)

This program generate time average and standard deviation of spherical harmonic coefficients which selected in the file [picked_sph_prefix].dat. In this program, file prefix [picked_sph_prefix] and start and end time are required in the interactive input. If data is end before the end time, the program will finish at the end of file. t_ave and t_sigma are added at the beginning of the input file name for the time average and standard deviation data file, respectively.
### Table 16: List of programs to take time average

<table>
<thead>
<tr>
<th>name</th>
<th>First input</th>
<th>Second input</th>
</tr>
</thead>
<tbody>
<tr>
<td>[vol_pwr_prefix]_s.dat</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_l.dat</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_m.dat</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>[vol_pwr_prefix]_lm.dat</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_s.dat</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_l.dat</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_m.dat</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>[layer_pwr_prefix]_lm.dat</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

### 18 Visualization using field data

The field data is written by XDMF or VTK data format using Cartesian coordinate. In this section we briefly introduce how to display the radial magnetic field using ParaView as an example.

After the starting ParaView, the file to be read is chosen in the file menu, and press "apply", button. Then, ParaView load the data from files (see Figure 12). Because the magnetic field is saved by the Cartesian coordinate, the radial magnetic field is obtained by the calculator tool. The procedure is as following (see Figure 13)

1. Push calculator button.
2. Choose "Point Data" in Attribute menu
3. Input data name for radial magnetic field ("B_r" in Figure 13)
4. Enter the equation to evaluate radial mantic field $B_r = \frac{\mathbf{B} \cdot \mathbf{r}}{|\mathbf{r}|}$.
5. Finally, push "Apply" button.

After obtaining the radial mantric field, the image in figure 14 is obtained by using "slice" and "Contour" tools with appropriate color mapping.
Figure 12: File open window for ParaView
Figure 13: File open window for ParaView

Figure 14: Visualization of radial magnetic field by Paraview.
References


Appendix A  Definition of parameters for control files

A.1  data_files_def

File names and number of processes and threads are defined in this block.

num_subdomain_ctl [Num_PE]
Number of subdomain for the MPI program [Num_PE] is defined by integer. If number of processes in mpirun -np is different from number of subdomains, program will be stopped with message.

num_smp_ctl [Num_Threads]
Number of SMP threads for OpenMP [Num_Threads] is defined by integer. You can set larger number than the actualumber of thread to be used. If actual number of thread is less than this number, number of threads is set to the number which is defined in this field.

sph_file_prefix [sph_prefix]
File prefix of spherical harmonics indexing and FEM mesh file [sph_prefix] is defined by text. Process ID and extension are added after this file prefix.

boundary_data_file_name [boundary_data_name]
File name of boundary condition data file [boundary_data_name] is defined by text.

restart_file_prefix [rst_prefix]
File prefix of spectrum data for restarting and snapshots [rst_prefix] is defined by text. Step number, process ID, and extension are added after this file prefix.

field_file_prefix [fld_prefix]
File prefix of field data for visualize snapshots [fld_prefix] is defined by text. Step number and file extension are added after this file prefix.

field_file_fmt_ctl [fld_format]
Field data field format for visualize snapshots [fld_format] is defined by text. The following formats are currently supported.
single_HDF5 Merged HDF5 file (Available if HDF5 library is linked)
single_VTK Merged VTK file (Default)
VTK Distributed VTK file

A.2 phys_values_ctl

Fields for the simulation are defined in this block.

array nod_value_ctl [Field] [Viz_flag] [Monitor_flag]  
Fields name [Field] for the simulation are listed in this array. If required fields for simulation are not in the list, simulation program adds required field in the list, but does not output any field data and monitoring data. [Viz_flag] is set to output of the field data for visualization by

Viz_On Write field data to VTK file
Viz_Off Do not write field data to VTK file.

In the [Monitor_flag], output in the monitoring data is defined by

Monitor_On Write spectrum into monitoring data
Monitor_Off Do not write spectrum into monitoring data

Supported field in the present version is listed in Table 17

A.3 time_evolution_ctl

Fields for time evolution are defined in this block.

array time_evo_ctl [Field]  
Fields name for time evolution are listed in this array in [Field] by text. Available fields are listed in Table 18

A.4 boundary_condition

Boundary condition are defined in this block.
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity</td>
<td>Velocity</td>
<td>$u$</td>
</tr>
<tr>
<td>vorticity</td>
<td>Vorticity</td>
<td>$\omega = \nabla \times u$</td>
</tr>
<tr>
<td>pressure</td>
<td>Pressure</td>
<td>$p$</td>
</tr>
<tr>
<td>temperature</td>
<td>Temperature</td>
<td>$T$</td>
</tr>
<tr>
<td>perturbation_temp</td>
<td>Perturbation of temperature</td>
<td>$\Theta = T - T_0$</td>
</tr>
<tr>
<td>heat_source</td>
<td>Heat source</td>
<td>$q_T$</td>
</tr>
<tr>
<td>composition</td>
<td>Composition variation</td>
<td>$C$</td>
</tr>
<tr>
<td>composition_source</td>
<td>Composition source</td>
<td>$q_C$</td>
</tr>
<tr>
<td>magnetic_field</td>
<td>Magnetic field</td>
<td>$B$</td>
</tr>
<tr>
<td>current_density</td>
<td>Current density</td>
<td>$J = \nabla \times B$</td>
</tr>
<tr>
<td>electric_field</td>
<td>Electric field</td>
<td>$E = \sigma (J - u \times B)$</td>
</tr>
<tr>
<td>inertia</td>
<td>Inertia term</td>
<td>$-\omega \times u$</td>
</tr>
<tr>
<td>viscous_diffusion</td>
<td>Viscous diffusion</td>
<td>$-\nu \nabla \times \nabla \times u$</td>
</tr>
<tr>
<td>buoyancy</td>
<td>Thermal buoyancy</td>
<td>$-\alpha_T T g$</td>
</tr>
<tr>
<td>composite_buoyancy</td>
<td>Compositional buoyancy</td>
<td>$-\alpha_C C g$</td>
</tr>
<tr>
<td>Lorentz_force</td>
<td>Lorentz force</td>
<td>$J \times B$</td>
</tr>
<tr>
<td>Coriolis_force</td>
<td>Coriolis force</td>
<td>$-2\Omega \hat{z} \times u$</td>
</tr>
<tr>
<td>thermal_diffusion</td>
<td>Thermal diffusion</td>
<td>$\kappa_T \nabla^2 T$</td>
</tr>
<tr>
<td>grad_temp</td>
<td>Temperature gradient</td>
<td>$\nabla T$</td>
</tr>
<tr>
<td>heat_flux</td>
<td>Advevtive heat flux</td>
<td>$uT$</td>
</tr>
<tr>
<td>heat_advect</td>
<td>Heat advection</td>
<td>$-u \cdot \nabla T = -\nabla \cdot (uT)$</td>
</tr>
<tr>
<td>composition_diffusion</td>
<td>Compositional diffusion</td>
<td>$\kappa_C \nabla^2 C$</td>
</tr>
<tr>
<td>grad_composition</td>
<td>Composition gradient</td>
<td>$\nabla C$</td>
</tr>
<tr>
<td>composite_flux</td>
<td>Advevtive composition flux</td>
<td>$uC$</td>
</tr>
<tr>
<td>composition_advect</td>
<td>Compositional advection</td>
<td>$-u \cdot \nabla C = -\nabla \cdot (uC)$</td>
</tr>
<tr>
<td>magnetic_diffusion</td>
<td>Magnetic diffusion</td>
<td>$-\eta \nabla \times \nabla \times B$</td>
</tr>
<tr>
<td>poynting_flux</td>
<td>Poynting flux</td>
<td>$E \times B$</td>
</tr>
<tr>
<td>rot_LOrentz_force</td>
<td>Curl of Lorentz force</td>
<td>$\nabla \times (J \times B)$</td>
</tr>
<tr>
<td>rot_Coriolis_force</td>
<td>Curl of Coriolis force</td>
<td>$-2\Omega \nabla \times (\hat{z} \times u)$</td>
</tr>
<tr>
<td>rot_buoyancy</td>
<td>Curl of thermal buoyancy</td>
<td>$-\nabla \times (\alpha_T T g)$</td>
</tr>
<tr>
<td>rot_composite_buoyancy</td>
<td>Curl of compositional buoyancy</td>
<td>$-\nabla \times (\alpha_C C g)$</td>
</tr>
<tr>
<td>buoyancy_flux</td>
<td>Buoyancy flux</td>
<td>$-\alpha_T T g \cdot u$</td>
</tr>
<tr>
<td>Lorentz_work</td>
<td>Work of Lorentz force</td>
<td>$u \cdot (J \times B)$</td>
</tr>
</tbody>
</table>
Table 18: List of field name for time evolution

<table>
<thead>
<tr>
<th>label</th>
<th>field name</th>
<th>Description</th>
<th>label</th>
<th>field name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity</td>
<td>Velocity</td>
<td>u</td>
<td>temperature</td>
<td>Temperature</td>
<td>T</td>
</tr>
<tr>
<td>composition</td>
<td>Composition variation</td>
<td>C</td>
<td>magnetic_field</td>
<td>Magnetic field</td>
<td>B</td>
</tr>
</tbody>
</table>

array bc.temperature [Group] [Type] [Value]
Boundary conditions for temperature are defined by this array. Position of boundary is defined in [Group] column by ICB or CMB. The following type of boundary conditions are available for temperature in [Type] column.

fixed Fixed homogeneous temperature on the boundary. The fixed value is defined in [Value] by real.

fixed_file Fixed temperature defined by external file. [Value] in this line is ignored. See section [10.3]

fixed_flux Fixed homogeneous heat flux on the boundary. The value is defined in [Value] by real. Positive value indicates outward flux from fluid shell. (e.g. Flux to center at ICB and Flux to mantle at CMB are positive.)

fixed_flux_file Fixed heat flux defined by external file. [Value] in this line is ignored. See section [10.3]

array bc.velocity [Group] [Type] [Value]
Boundary conditions for velocity are defined by this array. Position of boundary is defined in [Group] by ICB or CMB. The following boundary conditions are available for velocity in [Type] column.

non_slip_sph Non-slip boundary is applied to the boundary defined in [Group]. Real value is required in [Value], but they value is not used in the program.

free_slip_sph Free-slip boundary is applied to the boundary defined in [Group]. Real value is required in [Value], but they value is not used in the program.

rot_inner_core If this condition is set, inner core \((r < r_i)\) rotation is solved by using viscous torque and Lorentz torque. This boundary condition can be used for ICB,
and grid is filled to center. Real value is required in [Value], but they value is not used in the program.

**rot_x** Set constant rotation around $x$-axis in [Value] by real. Rotation vector can be defined with *rot_y* and *rot_z*.

**rot_y** Set constant rotation around $y$-axis in [Value] by real. Rotation vector can be defined with *rot_z* and *rot_x*.

**rot_z** Set constant rotation around $z$-axis in [Value] by real. Rotation vector can be defined with *rot_x* and *rot_y*.

**array bc_magnetic_field** [Group] [Type] [Value]
Boundary conditions for magnetic field are defined by this array. Position of boundary is defined in [Group] by to_center, ICB, or CMB. The following boundary conditions are available for magnetic field in [Type] column.

**insulator** Magnetic field is connected to potential field at boundary defined in [Group]. Real value is required at [Value], but they value is not used in the program.

**sph_to_center** If this condition is set, magnetic field in conductive inner core ($r < r_i$) is solved. This boundary condition can be used for ICB, and grid is filled to center. The value at [Value] does not used.

**array bc_composition** [Group] [Type] [Value]
Boundary conditions for composition variation are defined by this array. Position of boundary is defined in [Group] by ICB or CMB. The following boundary conditions are available for composition variation in [Type] column.

**fixed** Fixed homogeneous composition on the boundary. The fixed value is defined in [Value] by real.

**fixed_file** Fixed composition defined by external file. [Value] in this line is ignored. See section 10.3.

**fixed_flux** Fixed homogeneous compositional flux on the boundary. The value is defined in [Value] by real. Positive value indicates outward flux from fluid shell. (e.g. Flux to center at ICB and Flux to mantle at CMB are positive.)

**fixed_flux_file** Fixed compositional flux defined by external file. [Value] in this line is ignored. See section 10.3.
A.5 forces_define

Forces for the momentum equation are defined in this block.

array force_ctl [Force]
Name of forces for momentum equation are listed in [Force] by text. The following fields are available.

Table 19: List of force

<table>
<thead>
<tr>
<th>Label</th>
<th>Field name</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coriolis</td>
<td>Coriolis force</td>
<td>$-2\Omega \hat{z} \times u$</td>
</tr>
<tr>
<td>Lorentz</td>
<td>Lorentz force</td>
<td>$J \times B$</td>
</tr>
<tr>
<td>gravity</td>
<td>Thermal buoyancy</td>
<td>$-\alpha_T T g$</td>
</tr>
<tr>
<td>Composite_gravity</td>
<td>Compositional buoyancy</td>
<td>$-\alpha_C C g$</td>
</tr>
</tbody>
</table>

A.6 dimensionless_ctl

Dimensionless numbers are defined in this block.

array dimless_ctl [Name] [Value]
Dimensionless are listed in this array. The name is defined in [Name] by text, and value is defined in [Value] by real. These name of the dimensionless numbers are used to construct coefficients for each terms in governing equations. The following names can not be used because of reserved name in the program.

Table 20: List of reserved name of dimensionless numbers

<table>
<thead>
<tr>
<th>label</th>
<th>field name</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>zero</td>
<td>0.0</td>
</tr>
<tr>
<td>One</td>
<td>one</td>
<td>1.0</td>
</tr>
<tr>
<td>Two</td>
<td>two</td>
<td>2.0</td>
</tr>
<tr>
<td>Radial_35</td>
<td>Ratio of outer core thickness to whole core</td>
<td>$0.65 = 1 - 0.35$</td>
</tr>
</tbody>
</table>
A.7 coefficients_ctl

Coefficients of each term in governing equations are defined in this block. Each coefficients are defined by list of name of dimensionless number [Name] and its power [Power]. For example, coefficient for Coriolis term for the dynamo benchmark $2E^{-1}$ is defined as

```plaintext
array coef_4_Coriolis_ctl 2
  coef_4_Coriolis_ctl Two 1.0
  coef_4_Coriolis_ctl Ekman_number -1.0
end array coef_4_Coriolis_ctl
```

(Back to control MHD)

A.7.1 thermal

Coefficients of each term in heat equation are defined in this block.

(Back to control MHD)

```plaintext
c_coef_4_termal_ctl [Name] [Power]
Coefficient for evolution of temperature $\frac{\partial T}{\partial t}$ and advection of heat $(u \cdot \nabla) T$ is defined by this array.

c_coef_4_t_diffuse_ctl [Name] [Power]
Coefficient for thermal diffusion $\kappa T \nabla^2 T$ is defined by this array.

c_coef_4_heat_source_ctl [Name] [Power]
Coefficient for heat source $q_T$ is defined by this array.
```

A.7.2 momentum

Coefficients of each term in momentum equation are defined in this block.

(Back to control MHD)

```plaintext
c_coef_4_velocity_ctl [Name] [Power]
Coefficient for evolution of velocity $\frac{\partial u}{\partial t}$ (or $\frac{\partial \omega}{\partial t}$ for the vorticity equation) and advection $-\omega \times u$ (or $-\nabla \times (\omega \times u)$ for the vorticity equation) is defined by this array.
```
coef_4.press_ctl  [Name] [Power]
Coefficient for pressure gradient $-\nabla P$ is defined by this array. Pressure does not appear the vorticity equation which is used for the time integration. But this coefficient is used to evaluate pressure field.

c coef_4.v_diffuse_ctl  [Name] [Power]
Coefficient for viscous diffusion $-\nu \nabla \times \nabla \times \mathbf{u}$ is defined by this array.

c coef_4.buoyancy_ctl  [Name] [Power]
Coefficient for buoyancy $-\alpha T g$ is defined by this array.

c coef_4.Coriolis_ctl  [Name] [Power]
Coefficient for Coriolis force $-2\Omega \hat{z} \times \mathbf{u}$ is defined by this array.

c coef_4.Lorentz_ctl  [Name] [Power]
Coefficient for Lorentz force $\rho^{-1} J \times B$ is defined by this array.

c coef_4.composit_buoyancy_ctl  [Name] [Power]
Coefficient for compositional buoyancy $-\alpha C g$ is defined by this array.

A.7.3 induction

Coefficients of each term in magnetic induction equation are defined in this block.

Back to control_MHD

c coef_4.magnetic_ctl  [Name] [Power]
Coefficient for evolution of temperature $\frac{\partial B}{\partial t}$ is defined by this array.

c coef_4.m_diffuse_ctl  [Name] [Power]
Coefficient for magnetic diffusion $-\eta \nabla \times \nabla \times B$ is defined by this array.

c coef_4.induction_ctl  [Name] [Power]
Coefficient for magnetic induction $\nabla \times (u \times B)$ is defined by this array.
A.7.4 composition

Coefficients of each term in composition equation are defined in this block.

(Back to control_MHD)

c coef_4.composition_ctl  [Name] [Power]
Coefficient for evolution of composition variation \( \frac{\partial C}{\partial t} \) and advection of heat \((u \cdot \nabla) C\) is defined by this array.

c coef_4.c_diffuse_ctl  [Name] [Power]
Coefficient for compositional diffusion \( \kappa_C \nabla^2 C \) is defined by this array.

c coef_4.composition_source_ctl  [Name] [Power]
Coefficient for composition source \( q_C \) is defined by this array.

A.8 temperature_define

Reference of temperature \( T_0 \) is defined in this block. If reference of temperature is defined, perturbation of temperature \( \Theta = T - T_0 \) is used for time evolution and buoyancy.

(Back to control_MHD)

c ref_temp_ctl  [REFERENCE_TEMP]
Type of reference temperature is defined by text. The following options are available for [REFERENCE_TEMP].

c none Reference of temperature is not defined. Temperature \( T \) is used to time evolution and thermal buoyancy.

c spherical_shell Reference of temperature is set by

\[
T_0 = \frac{1}{(r_h - r_l)} \left[ r_l T_l - r_h T_h + \frac{r_l r_h}{r} (T_h - T_l) \right].
\]

c low_temp_ctl Amplitude of low reference temperature \( T_l \) and its radius \( r_l \) (Generally \( r_l = r_o \)) are defined in this block.

c high_temp_ctl Amplitude of high reference temperature \( T_h \) and its radius \( r_h \) (Generally \( r_h = r_i \)) are defined in this block.
depth  [RADIUS]
Radius for reference temperature is defined by real.

temperature  [TEMPERATURE]
Temperature for reference temperature is defined by real.

A.9  time_step_ctl
Time stepping parameters are defined in this block.

elapsed_time_ctl  [ELAPSED_TIME]
Elapsed (wall clock) time (second) for simulation [ELAPSED_TIME] is defined by real. This parameter varies if end step [ISTEP_FINISH] is defined to \(-1\). If simulation runs for given time, program output spectrum data [rst_prefix].elaps.[process #].fst immediately, and finish the simulation.

i_step_init_ctl  [ISTEP_START]
Start step of simulation [ISTEP_START] is defined by integer. If [ISTEP_START] is set to \(-1\) and [INITIAL_TYPE] is set to start_from_rst_file, program read spectrum data file [rst_prefix].elaps.[process #].fst and start the simulation.

i_step_finish_ctl  [ISTEP_FINISH]
End step of simulation [ISTEP_FINISH] is defined by integer. If this value is set to \(-1\), simulation stops when elapsed time reaches to [ELAPSED_TIME].

i_step_check_ctl  [ISTEP_MONITOR]
Increment of time step for monitoring data [ISTEP_MONITOR] is defined by integer.

i_step_rst_ctl  [ISTEP_RESTART]
Increment of time step to output spectrum data for restarting [ISTEP_RESTART] is defined by integer.
i_step_field_ctl  [ISTEP_FIELD]
Increment of time step to output field data for visualization [ISTEP_FIELD] is defined by integer. If [ISTEP_FIELD] is set to be 0, no field data are written.

i_step_sectioning_ctl  [ISTEP_SECTION]
Increment of time step to output cross section data for visualization [ISTEP_SECTION] is defined by integer. If [ISTEP_SECTION] is set to be 0, no cross section data are written.

i_step_isosurface_ctl  [ISTEP_ISOSURFACE]
Increment of time step to output isosurface data for visualization [ISTEP_ISOSURFACE] is defined by integer. If [ISTEP_ISOSURFACE] is set to be 0, no isosurface data are written.

dt_ctl  [DELTA_TIME]
Length of time step $\Delta t$ is defined by real value.

time_init_ctl  [INITIAL_TIME]
Initial time $t_0$ is defined by real value. This value is ignored if simulation starts from restart data.

A.10  new_time_step_ctl
Time stepping parameters to update initial data are defined in this block. Items in this block is the same as [i_step_field_ctl] (Back to control_assemble_sph)

A.11  restart_file_ctl
Initial field for simulation is defined in this block.
(Back to control_MHD)

rst_ctl  [INITIAL_TYPE]
Type of Initial field is defined by text. The following parameters are available for [INITIAL_TYPE].

No_data No initial data file. Small temperature perturbation and seed magnetic field are set as an initial field.
Initial field is read from spectrum data file. File prefix is defined by `restart_file_prefix`.

**Dynamo_benchmark_0** Generate initial field for dynamo benchmark case 0

**Dynamo_benchmark_1** Generate initial field for dynamo benchmark case 1

**Dynamo_benchmark_2** Generate initial field for dynamo benchmark case 2

**Pseudo_vacuum_benchmark** Generate initial field for pseudo vacuum dynamo benchmark

### A.12 time_loop.ctl

Time evolution scheme is defined in this block.

(Back to control_MHD)

**scheme_ctl** `[EVOLUTION_SCHEME]`

Time evolution scheme is defined by text. Currently, Crank-Nicolson scheme is only available for diffusion terms.

- **Crank_Nicolson** Crank-Nicolson scheme for diffusion terms and second order Adams-Bashforth scheme the other terms.

**coef_imp_v_ctl** `[COEF_INP_U]`

Coefficients for the implicit parts of the Crank-Nicolson scheme for viscous diffusion `[COEF_INP_U]` is defined by real.

**coef_imp_t_ctl** `[COEF_INP_T]`

Coefficients for the implicit parts of the Crank-Nicolson scheme for thermal diffusion `[COEF_INP_T]` is defined by real.

**coef_imp_b_ctl** `[COEF_INP_B]`

Coefficients for the implicit parts of the Crank-Nicolson scheme for magnetic diffusion `[COEF_INP_B]` is defined by real.

**coef_imp_c_ctl** `[COEF_INP_C]`

Coefficients for the implicit parts of the Crank-Nicolson scheme for compositional diffusion `[COEF_INP_C]` is defined by real.
FFT_library_ctl [FFT_Name]
FFT library name for Fourier transform is defined by text. The following libraries are available for [FFT_Name]. If this flag is not defined, program searches the fastest library in the initialization process.

FFTW Use FFTW

FFTPACK Use FFTPACK

Legendre_trans_loop_ctl [FFT_Name]
Loop configuration for Legendre transform is defined by text. The following settings are available for [Leg_Loop]. If this flag is not defined, program searches the fastest approach in the initialization process.

Inner_radial_loop Loop for the radial grids is set as the innermost loop

Outer_radial_loop Loop for the radial grids is set as the outermost loop

Long_loop Long one-dimensional loop is used

A.13 sph_monitor_ctl

Monitoring data is defined in this block. Monitoring data output (mean square, average, Gauss coefficients, or specific components of spectrum data) are flagged by Monitor_On in nod_value_ctl array.

volume_average_prefix [vol_ave_prefix]
File prefix for volume average data [vol_ave_prefix] is defined by Text. Program add .dat extension after this file prefix. If this file prefix is not defined, volume average data are not generated.

volume_pwr.spectr.prefix [vol_pwr_prefix]
File prefix for mean square spectrum data averaged over the fluid shell [vol_pwr_prefix] is defined by Text. Spectrum as a function of degree l is written in [vol_pwr_prefix]_l.dat, spectrum as a function of order m is written in [vol_pwr_prefix]_m.dat, and spectrum as a function of (l−m) is written in [vol_pwr_prefix]_lm.dat. This prefix is also used for the file name of the volume mean square data as [vol_pwr_prefix]_s.dat.
If this file prefix is not defined, volume spectrum data are not generated and volume mean square data is written as sph_pwr_volume_s.dat.

layered_pwr_spectr_prefix  [layer_pwr_prefix]
File prefix for mean square spectrum data averaged over each sphere surface [layer_pwr_prefix] is defined by Text.

Spectrum as a function of degree l is written in [layer_pwr_prefix]_l.dat, spectrum as a function of order m is written in [layer_pwr_prefix]_m.dat, and spectrum as a function of \((l - m)\) is written in [layer_pwr_prefix]_lm.dat. If this file prefix is not defined, sphere averaged spectrum data are not generated.

picked_sph_prefix  [picked_sph_prefix]
File prefix for picked spectrum data [picked_sph_prefix] is defined by Text. Program add .dat extension after this file prefix. If this file prefix is not defined, picked spectrum data are not generated.

gauss_coefs_prefix  [gauss_coef_prefix]
File prefix for Gauss coefficients [gauss_coef_prefix] is defined by Text. Program add .dat extension after this file prefix. If this file prefix is not defined, Gauss coefficients data are not generated.

gauss_coefs_radius_ctl  [gauss_coef_radius]
Normalized radius to obtain Gauss coefficients [gauss_coef_radius] is defined by real. Gauss coefficients are evaluated from the poloidal magnetic field at CMB by assuming electrically insulated mantle. Do not set [gauss_coef_radius] less than the outer core radius \(r_o\).

nusselt_number_prefix  [nusselt_number_prefix]
File prefix for Nusselt number data at ICB and CMB [nusselt_number_prefix] is defined by Text. Program add .dat extension after this file prefix. If this file prefix is not defined, Nusselt number data are not generated.

CAUTION: Nusselt number is not evaluated if heat source exists.

array spectr_layer_ctl  [Layer #] List of radial grid point number [Layer #] to output power spectrum data by integer. If this array is not defined, layered mean square data are written for all radial grid points.
array pick_layer_ctl  [Layer #] List of radial grid point number [Layer #] to output picked spectrum data by integer. If this array is not defined, picked spectrum data are written for all radial grid points.

array pick_sph_spectr_ctl  [Degree]  [Order] List of spherical harmonics mode $l$ and $m$ of spectrum data to output. [Degree] and [Order] are defined by integer.

array pick_sph_degree_ctl  [Degree] Degrees $l$ to output spectrum data are listed in [Degree] by integer. All spectrum data with listed degree $l$ is output in file.

array pick_sph_order_ctl  [Order] Order $m$ to output spectrum data are listed in [Order] by integer. All spectrum data with listed order $m$ is output in file.

array pick_gauss_coefs_ctl  [Degree]  [Order] List of spherical harmonics mode $l$ and $m$ of Gauss coefficients to output. [Degree] and [Order] are defined by integer.

array pick_gauss_coef_degree_ctl  [Degree] Degrees $l$ to output Gauss coefficients are listed in [Degree] by integer. All Gauss coefficients with listed $l$ is output in file.

array pick_gauss_coef_order_ctl  [Order] Orders $m$ to output Gauss coefficients are listed in [Order] by integer. All Gauss coefficients with listed order $m$ is output in file.

nphi_mid_eq_ctl  [Nphi_mid_equator] Number of grid points [Nphi_mid_equator] in longitudinal direction to evaluate mid-depth of the shell in the equatorial plane for dynamo benchmark is defined as integer. If [Nphi_mid_equator] is not defined or less than zero, [Nphi_mid_equator] is set set number grid as the input spherical transform data.
A.14  visual_control

Visualization modules are defined in this block. Parameters for cross sections and isosurfaces are defined in this block.

(Back to visual_control)

A.15  cross_section_ctl

Control parameters for cross sectioning are defined in this block.

(Back to cross_section_ctl)

section_file_prefix  [file_prefix]
File prefix for cross section data is defined as character [file_prefix].

A.15.1  surface_define

Each cross section is defined in this block.

(Back to cross_section_ctl)

section_method  [METHOD]
Method of the cross sectioning is defined as character [METHOD]. Supported cross section is shown in Table 21.

Table 21: Supported cross sections

<table>
<thead>
<tr>
<th>[METHOD]</th>
<th>Surface type</th>
</tr>
</thead>
<tbody>
<tr>
<td>equation</td>
<td>Quadrature surface</td>
</tr>
<tr>
<td>plane</td>
<td>Plane surface</td>
</tr>
<tr>
<td>sphere</td>
<td>Sphere</td>
</tr>
<tr>
<td>ellipsoid</td>
<td>Ellipsoid</td>
</tr>
</tbody>
</table>

coefs_ctl  [TERM] [COEFFICIENT]
This array defines coefficients for a quadrature surface described by

\[ ax^2 + by^2 + cz^2 + dyz + ezx + fxy + gx + hy + jz + k = 0. \]
Each coefficient $a$ to $k$ are defined by the name of the term [TERM] and real value [COEFFICIENT] as shown in Table \ref{tab:coefficients}.

Table 22: List of coefficient labels for quadrature surface

<table>
<thead>
<tr>
<th>TERM</th>
<th>Defined value</th>
<th>TERM</th>
<th>Defined value</th>
<th>TERM</th>
<th>Defined value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x^2$</td>
<td>$a$</td>
<td>$y^2$</td>
<td>$b$</td>
<td>$z^2$</td>
<td>$c$</td>
</tr>
<tr>
<td>$yz$</td>
<td>$d$</td>
<td>$zx$</td>
<td>$e$</td>
<td>$xy$</td>
<td>$f$</td>
</tr>
<tr>
<td>$x$</td>
<td>$g$</td>
<td>$y$</td>
<td>$h$</td>
<td>$z$</td>
<td>$i$</td>
</tr>
<tr>
<td>const</td>
<td>$h$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

radius [SIZE] defines radius $r$ for a sphere surface defined by

$$\left( x - x_0 \right)^2 + \left( y - y_0 \right)^2 + \left( z - z_0 \right)^2 = r^2.$$  

normal_vector [DIRECTION] [COMPONENT]  
This array defines normal vector $(a, b, c)$ for a plane surface described by

$$a (x - x_0) + b (y - y_0) + c (z - z_0) = 0.$$  

Each component is defined by [DIRECTION] and real value [COMPONENT] as shown in Table \ref{tab:vector}.

Table 23: List of coefficient labels for vector

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>Defined value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>$a$</td>
</tr>
<tr>
<td>$y$</td>
<td>$b$</td>
</tr>
<tr>
<td>$z$</td>
<td>$c$</td>
</tr>
</tbody>
</table>

axial_length [DIRECTION] [COMPONENT]  
This array defines size $(a, b, c)$ of an ellipsoid surface described by

$$\left( \frac{x - x_0}{a} \right)^2 + \left( \frac{y - y_0}{b} \right)^2 + \left( \frac{z - z_0}{c} \right)^2 = 1.$$  

94
Each component is defined by [DIRECTION] and real value [COMPONENT] as shown in Table 23.

center_position [DIRECTION] [COMPONENT]
Position of center \((x_0, y_0, z_0)\) of sphere or ellipsoid is defined this array. Position on a plane surface \((x_0, y_0, z_0)\) is also defined. Each component is defined by [DIRECTION] and real value [COMPONENT] as shown in Table 24.

<table>
<thead>
<tr>
<th>[DIRECTION]</th>
<th>Defined value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>(x_0)</td>
</tr>
<tr>
<td>(y)</td>
<td>(y_0)</td>
</tr>
<tr>
<td>(z)</td>
<td>(z_0)</td>
</tr>
</tbody>
</table>

Table 24: List of coefficient labels for vector

section_area_ctl Areas for the cross sectioning are defined in this array. The following groups can be defined in this block.

- **outer_core** Outer core.
- **inner_core** Inner core (If exist).
- **external** External of the core (If exist).
- **all** Whole simulation domain.

A.15.2 output_field_define

Field data on the cross section are defined in this block.

output_field Field informations for cross section are defined in this array. Name of the output fields is defined by [FIELD], and component of the fields is defined by [COMPONENT]. Labels of the field name are listed in Table 17 and labels of the component are listed in Table 25.
Table 25: List of field type for cross sectioning and isosurface module

<table>
<thead>
<tr>
<th>[COMPONENT]</th>
<th>Field type</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>scalar field</td>
</tr>
<tr>
<td>vector</td>
<td>Cartesian vector field</td>
</tr>
<tr>
<td>x</td>
<td>x-component</td>
</tr>
<tr>
<td>y</td>
<td>y-component</td>
</tr>
<tr>
<td>z</td>
<td>z-component</td>
</tr>
<tr>
<td>radial</td>
<td>radial (r-) component</td>
</tr>
<tr>
<td>theta</td>
<td>θ-component</td>
</tr>
<tr>
<td>phi</td>
<td>φ-component</td>
</tr>
<tr>
<td>cylinder_r</td>
<td>cylindrical radial (s-) component</td>
</tr>
<tr>
<td>magnitude</td>
<td>magnitude of vector</td>
</tr>
</tbody>
</table>

isosurface_file_prefix [file_prefix]
File prefix for isosurface data is defined as character [file_prefix].

A.15.3 isosurf_define

Each isosurface is defined in this block.

(Back to isosurface_ctl)

isosurf_field Field name for isosurface is defined by [FIELD]. Labels of the field name are listed in Table 17.

isosurf_component Component name for isosurface is defined by [COMPONENT]. Labels of the component are listed in Table 25.

isosurf_value Isosurface value is defined as real value VALUE.

isosurf_area_ctl Areas for the isosurfacing are defined in this array. The same groups can be defined as section_area_ctl.
A.15.4  field_on_isosurf

Field data on the isosurface are defined in this block.

(result_type) Output data type is defined by [TYPE]. Following types can be defined:
constant  Constant value is set as a result field. The amplitude is set by result_value.
field  Field data on the isosurface are written. Fields to be written are defined by output_field array.

(result_value) Isosurface value is defined as real value VALUE.

(output_field) Field informations for cross section are defined in this array. Name of the output fields is defined by [FIELD], and component of the fields is defined by [COMPONENT]. Labels of the field name are listed in Table 17 and labels of the component are listed in Table 25.

A.16  num_domain_ctl

Parallelization is defined in this block. Domain decomposition is defined for spectrum data, field data, and Legendre transform.

(num_radial_domain_ctl) Number of subdomains in the radial direction for the spherical grid (r, θ, φ) and spherical transforms (r, θ, m) and (r, l, m).

(num_horizontal_domain_ctl) Number of subdomains in the horizontal direction. The number will be the number of subdomains for the meridional directions for the spherical grid (r, θ, φ) and Fourier transform (r, θ, m). For Legendre transform (r, θ, m) and (r, l, m), the number will be the number of subdomains for the harmonics order m.
num_domain.sph_grid  [Direction] [Ndomain]
Definition of number of subdomains for physical data in spherical coordinate \((r, \theta, \phi)\). Direction radial or meridional is set in [Direction], and number of subdomains [Ndomain] are defined in the integer field.

num_domain.legendre  [Direction] [Ndomain]
Definition of number of subdomains for Legendre transform between \((r, \theta, m)\) and \((r, l, m)\). Direction radial or zonal is set in [Direction], and number of subdomains [Ndomain] are defined in the integer field.

num_domain.spectr  [Direction] [Ndomain]
Definition of number of subdomains for spectrum data in \((r, l, m)\). Direction modes is set in the [Direction] field, and number of subdomains [Ndomain] are defined in the integer field.

A.17  num_grid.sph
Spatial resolution of the spherical shell is defined in this block.

[Back to control.sph.shell]

truncation_level_ctl  [Lmax]
Truncation level \(L\) is defined by integer. Spherical harmonics is truncated by triangular \(0 \leq l \leq L\) and \(0 < m < l\).

ngrid.meridonal_ctl  [Ntheta]
Number of grid in the meridional direction [Ntheta] is defined by integer.

ngrid.zonal_ctl  [Nphi]
Number of grid in the zonal direction [Nphi] is defined by integer.

raidal_grid_type_ctl  [explicit, Chebyshev, or equi_distance]
Type of the radial grid spacing is defined by text. The following types are supported in Calypso.

   explicit  Equi-distance grid

   Chebyshev  Chebyshev collocation points

   equi_distance  Set explicitly by r_layer array

 98
num_fluid_grid_ctl  [Nr_shell]
(This option works with radial_grid_type_ctl is explicit or Chebyshev.) Number of layer in the fluid shell [Nr_shell] is defined by integer. Number of grids including CMB and ICB will be ([Nr_shell] + 1).

fluid_core_size_ctl  [Length]
(This option works with radial_grid_type_ctl is explicit or Chebyshev.) Size of the outer core [Length] (= r_o − r_i) is defined by real.

ICB_to_CMB_ratio_ctl  [R_ratio]
(This option works with radial_grid_type_ctl is explicit or Chebyshev.) Ratio of the inner core radius to outer core [R_ratio] (= r_i/r_o) is defined by real.

Min_radius_ctl  [Rmin]
(This option works with radial_grid_type_ctl is explicit or Chebyshev.) Minimum radius of the domains [Rmin] is defined by real. If this value is not defined, ICB becomes inner boundary of the domain.

Max_radius_ctl  [Rmax]
(This option works with radial_grid_type_ctl is explicit or Chebyshev.) Maximum radius of the domains [Rmax] is defined by real. If this value is not defined, CMB becomes outer boundary of the domain.

r_layer  [Layer #]  [Radius]
(This option works with [radial_grid_type_ctl] is explicit.) List of the radial grid points in the simulation domain. Index of the radial point [Layer #] is defined by integer, and radius [Radius] is defined by real.

array_boundaries_ctl  [Boundary_name]  [Layer #]
(This option works with [radial_grid_type_ctl] is explicit.) Boundaries of the simulation domain is defined by [Layer #] in [r_layer] array. The following boundary name can be defined for [Boundary_name].

to_Center Inner boundary of the domain to fill the center.

ICB  ICB
CMB  CMB
A.18  new_data_files_def

File names and number of processes for new domain decomposed data are defined in this block.

(num_new_domain_ctl [new_num_domain]
Number of subdomain for new decomposed data [new_num_domain] is defined by integer.

new_sph_mode_prefix [new_sph_prefix]
File prefix of new spherical harmonics indexing [new_sph_prefix] is defined by text.

new_restart_prefix [new_rst_prefix]
File prefix of new spectrum data [new_rst_prefix] is defined by text.

delete_original_data_flag [delete_original_data_flag]
If this flag set to YES, original spectrum data is deleted at the end of program.

A.19  newrst_magne_ctl

Parameters to modify magnetic field are defined in this block.

(magnetic_field_ratio_ctl [ratio]
Ratio of new magnetic field data to original magnetic field [ratio] is defined by real.)
Appendix B  GNU GENERAL PUBLIC LICENSE

Copyright © 1989, 1991 Free Software Foundation, Inc.

51 Franklin Street, Fifth Floor, Boston, MA 02110-1301, USA

Everyone is permitted to copy and distribute verbatim copies of this license document,
but changing it is not allowed.

Preamble

The licenses for most software are designed to take away your freedom to share and
change it. By contrast, the GNU General Public License is intended to guarantee your
freedom to share and change free software—to make sure the software is free for all its
users. This General Public License applies to most of the Free Software Foundation's
software and to any other program whose authors commit to using it. (Some other Free
Software Foundation software is covered by the GNU Library General Public License
instead.) You can apply it to your programs, too.

When we speak of free software, we are referring to freedom, not price. Our General
Public Licenses are designed to make sure that you have the freedom to distribute copies
of free software (and charge for this service if you wish), that you receive source code or
can get it if you want it, that you can change the software or use pieces of it in new free
programs; and that you know you can do these things.

To protect your rights, we need to make restrictions that forbid anyone to deny you
these rights or to ask you to surrender the rights. These restrictions translate to certain
responsibilities for you if you distribute copies of the software, or if you modify it.

For example, if you distribute copies of such a program, whether gratis or for a fee,
you must give the recipients all the rights that you have. You must make sure that they,
too, receive or can get the source code. And you must show them these terms so they know
their rights.

We protect your rights with two steps: (1) copyright the software, and (2) offer you this
license which gives you legal permission to copy, distribute and/or modify the software.

Also, for each author’s protection and ours, we want to make certain that everyone
understands that there is no warranty for this free software. If the software is modified by
someone else and passed on, we want its recipients to know that what they have is not the
original, so that any problems introduced by others will not reflect on the original authors’
reputations.

Finally, any free program is threatened constantly by software patents. We wish to
avoid the danger that redistributors of a free program will individually obtain patent li-
licenses, in effect making the program proprietary. To prevent this, we have made it clear that any patent must be licensed for everyone’s free use or not licensed at all.

The precise terms and conditions for copying, distribution and modification follow.

**TERMS AND CONDITIONS FOR COPYING, DISTRIBUTION AND MODIFICATION**

0. This License applies to any program or other work which contains a notice placed by the copyright holder saying it may be distributed under the terms of this General Public License. The “Program”, below, refers to any such program or work, and a “work based on the Program” means either the Program or any derivative work under copyright law: that is to say, a work containing the Program or a portion of it, either verbatim or with modifications and/or translated into another language. (Hereinafter, translation is included without limitation in the term “modification”.) Each licensee is addressed as “you”.

Activities other than copying, distribution and modification are not covered by this License; they are outside its scope. The act of running the Program is not restricted, and the output from the Program is covered only if its contents constitute a work based on the Program (independent of having been made by running the Program). Whether that is true depends on what the Program does.

1. You may copy and distribute verbatim copies of the Program’s source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice and disclaimer of warranty; keep intact all the notices that refer to this License and to the absence of any warranty; and give any other recipients of the Program a copy of this License along with the Program.

You may charge a fee for the physical act of transferring a copy, and you may at your option offer warranty protection in exchange for a fee.

2. You may modify your copy or copies of the Program or any portion of it, thus forming a work based on the Program, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:

   (a) You must cause the modified files to carry prominent notices stating that you changed the files and the date of any change.
(b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License.

(c) If the modified program normally reads commands interactively when run, you must cause it, when started running for such interactive use in the most ordinary way, to print or display an announcement including an appropriate copyright notice and a notice that there is no warranty (or else, saying that you provide a warranty) and that users may redistribute the program under these conditions, and telling the user how to view a copy of this License. (Exception: if the Program itself is interactive but does not normally print such an announcement, your work based on the Program is not required to print an announcement.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Program, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Program, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Program.

In addition, mere aggregation of another work not based on the Program with the Program (or with a work based on the Program) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may copy and distribute the Program (or a work based on it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you also do one of the following:

(a) Accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,

(b) Accompany it with a written offer, valid for at least three years, to give any third party, for a charge no more than your cost of physically performing source distribution, a complete machine-readable copy of the corresponding source
code, to be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange; or,

(c) Accompany it with the information you received as to the offer to distribute corresponding source code. (This alternative is allowed only for noncommercial distribution and only if you received the program in object code or executable form with such an offer, in accord with Subsection b above.)

The source code for a work means the preferred form of the work for making modifications to it. For an executable work, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the executable. However, as a special exception, the source code distributed need not include anything that is normally distributed (in either source or binary form) with the major components (compiler, kernel, and so on) of the operating system on which the executable runs, unless that component itself accompanies the executable.

If distribution of executable or object code is made by offering access to copy from a designated place, then offering equivalent access to copy the source code from the same place counts as distribution of the source code, even though third parties are not compelled to copy the source along with the object code.

4. You may not copy, modify, sublicense, or distribute the Program except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense or distribute the Program is void, and will automatically terminate your rights under this License. However, parties who have received copies, or rights, from you under this License will not have their licenses terminated so long as such parties remain in full compliance.

5. You are not required to accept this License, since you have not signed it. However, nothing else grants you permission to modify or distribute the Program or its derivative works. These actions are prohibited by law if you do not accept this License. Therefore, by modifying or distributing the Program (or any work based on the Program), you indicate your acceptance of this License to do so, and all its terms and conditions for copying, distributing or modifying the Program or works based on it.

6. Each time you redistribute the Program (or any work based on the Program), the recipient automatically receives a license from the original licensor to copy, distribute or modify the Program subject to these terms and conditions. You may not impose any further restrictions on the recipients’ exercise of the rights granted herein. You are not responsible for enforcing compliance by third parties to this License.
7. If, as a consequence of a court judgment or allegation of patent infringement or for any other reason (not limited to patent issues), conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot distribute so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not distribute the Program at all. For example, if a patent license would not permit royalty-free redistribution of the Program by all those who receive copies directly or indirectly through you, then the only way you could satisfy both it and this License would be to refrain entirely from distribution of the Program.

If any portion of this section is held invalid or unenforceable under any particular circumstance, the balance of the section is intended to apply and the section as a whole is intended to apply in other circumstances.

It is not the purpose of this section to induce you to infringe any patents or other property right claims or to contest validity of any such claims; this section has the sole purpose of protecting the integrity of the free software distribution system, which is implemented by public license practices. Many people have made generous contributions to the wide range of software distributed through that system in reliance on consistent application of that system; it is up to the author/donor to decide if he or she is willing to distribute software through any other system and a licensee cannot impose that choice.

This section is intended to make thoroughly clear what is believed to be a consequence of the rest of this License.

8. If the distribution and/or use of the Program is restricted in certain countries either by patents or by copyrighted interfaces, the original copyright holder who places the Program under this License may add an explicit geographical distribution limitation excluding those countries, so that distribution is permitted only in or among countries not thus excluded. In such case, this License incorporates the limitation as if written in the body of this License.

9. The Free Software Foundation may publish revised and/or new versions of the General Public License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies a version number of this License which applies to it and “any later version”, you have the option of following the terms and conditions either of that version or of any later version published by the Free Software Foundation. If the Program does not specify otherwise,
a version number of this License, you may choose any version ever published by the Free Software Foundation.

10. If you wish to incorporate parts of the Program into other free programs whose distribution conditions are different, write to the author to ask for permission. For software which is copyrighted by the Free Software Foundation, write to the Free Software Foundation; we sometimes make exceptions for this. Our decision will be guided by the two goals of preserving the free status of all derivatives of our free software and of promoting the sharing and reuse of software generally.

**NO WARRANTY**

11. **Because the Program is licensed free of charge, there is no warranty for the Program, to the extent permitted by applicable law.** Except when otherwise stated in writing the copyright holders and/or other parties provide the Program “as is” without warranty of any kind, either expressed or implied, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. The entire risk as to the quality and performance of the program is with you. Should the program prove defective, you assume the cost of all necessary servicing, repair or correction.

12. **In no event unless required by applicable law or agreed to in writing will any copyright holder, or any other party who may modify and/or redistribute the program as permitted above, be liable to you for damages, including any general, special, incidental or consequential damages arising out of the use or inability to use the program (including but not limited to loss of data or data being rendered inaccurate or losses sustained by you or third parties or a failure of the program to operate with any other programs), even if such holder or other party has been advised of the possibility of such damages.**

**END OF TERMS AND CONDITIONS**
Appendix: How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the “copyright” line and a pointer to where the full notice is found.

one line to give the program’s name and a brief idea of what it does.
Copyright (C) yyyy name of author

This program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 2 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details.

You should have received a copy of the GNU General Public License along with this program; if not, write to the Free Software Foundation, Inc., 51 Franklin Street, Fifth Floor, Boston, MA 02110-1301, USA.

Also add information on how to contact you by electronic and paper mail.
If the program is interactive, make it output a short notice like this when it starts in an interactive mode:

Gnomovision version 69, Copyright (C) yyyy name of author
Gnomovision comes with ABSOLUTELY NO WARRANTY; for details type ‘show w’.
This is free software, and you are welcome to redistribute it under certain conditions; type ‘show c’ for details.

The hypothetical commands show w and show c should show the appropriate parts of the General Public License. Of course, the commands you use may be called something other than show w and show c; they could even be mouse-clicks or menu items—whatever suits your program.
You should also get your employer (if you work as a programmer) or your school, if any, to sign a “copyright disclaimer” for the program, if necessary. Here is a sample; alter the names:

Yoyodyne, Inc., hereby disclaims all copyright interest in the program
‘Gnomovision’ (which makes passes at compilers) written by James Hacker.

signature of Ty Coon, 1 April 1989
Ty Coon, President of Vice

This General Public License does not permit incorporating your program into proprietary programs. If your program is a subroutine library, you may consider it more useful to permit linking proprietary applications with the library. If this is what you want to do, use the GNU Library General Public License instead of this License.