SAND2008-2681C

Robust, Extensible Representation of Complex Earth Models for Use in Seismological Software Systems

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Sponsored by National Nuclear Security Administration, Office of Nonproliferation Research and Engineering, Office of Defense Nuclear Nonproliferation, Contract No. DE-AC04-94AL85000

Objective

Develop an Earth model system capable of representing most Earth model structures in use today and extend that system to incorporate a broader range of local to global scale variable resolution models.

Introduction

Models of geophysically important properties of the Earth, such as seismic velocity, Q and density, can become large and complex when those properties vary in three dimensions within the model. We have developed an efficient, extensible, object oriented software framework that can accommodate a wide range of local to global scale 3D Earth models with grid resolutions that can vary widely throughout the model. In this paper, we describe some of the important characteristics, limitations and advantages of several types of grid topologies that might be used to represent geophysical properties within and Earth model.

Within a model, the surface of the Earth can be represented by a sphere, an ellipsoid or the topographic/bathymetric surface. In our representation geophysical properties are defined on a grid of nodes which are connected into a 3D topology in one of four fundamental ways. In fully *structured* models, grid nodes coincide with equally spaced lines of constant latitude, longitude and depth. Slightly more complex are models which are structured in the geographic dimensions but *layered* in the radial direction. Considerable flexibility is gained with *layered* models that are *unstructured* in the horizontal dimensions. These models may be comprised of triangles or quadrilaterals that tessellate the surface of Earth and allow resolution to vary in the horizontal dimensions. In the most general case, a fully *unstructured* 3D grid of nodes is tessellated using tetrahedrons, hexahedrons or other simple polyhedra. These models allow the most flexibility in terms of internal property variability and model resolution.

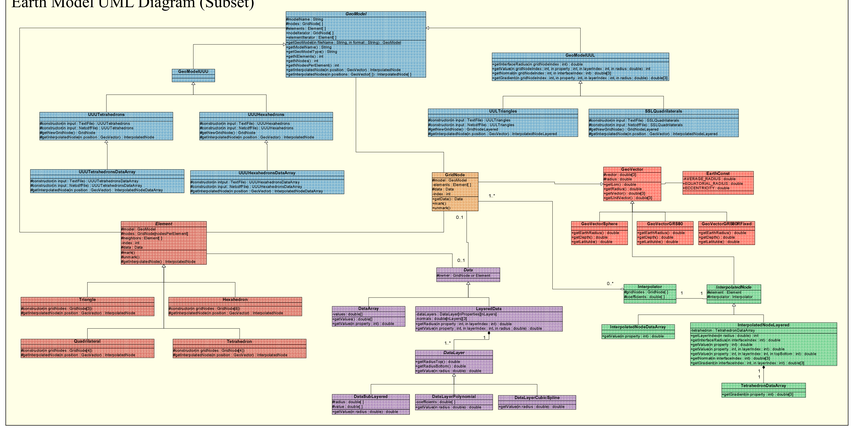
Earth Model Representation:

- Define one or more ***Grid*** objects that serve to partition the physical domain into discretized volume elements
- Associate ***Data*** objects defined on Grid nodes and/or cells containing the model attributes or interpolatory meta-data
- Define one or more ***Interpolator*** objects used to interpolate model attributes within volume elements
- Serve as the implementation for a ***Model*** interface used by Predictor and Optimizer objects

Data:
- Base class container of node and/or cell based model attribute data or interpolatory metadata
- Concrete derived types are specifically designed for various ***Interpolator*** / ***Grid*** combinations

Interpolator:
- Various concrete implementations exist including
  - Linear
  - Polynomial
  - Spline
  - Kriging
  - Moving Least Squares
  - Etc.
- Utilizes ***Data*** objects for additional metadata storage or interpolation process information when required
- Interpolates node or cell based model attributes at arbitrary locations

Earth Model UML Diagram (Subset)



Grid:

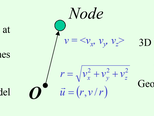
- Composed of components defining domain geometry (***Node*** objects) and topology (***Cell*** objects … and ***Edge***, ***Face*** objects in dynamic grids only)
- Primary function: Perform point containment searching and grid component adjacency discovery

- Categorize arbitrary grid representations into 4 different model types including:
  - SSS: Structured latitude/longitude/depth
  - SSL: Structured geographic surface grid decoupled from an arbitrary layer depth profile
  - UUL: Unstructured geographical surface grid decoupled from an arbitrary layer depth profile
  - UUU: Unstructured volumetric Cartesian grid

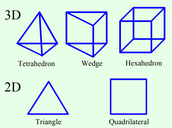
Advantages / Disadvantages

Grid Type	Global	Multi-resolution	Point search	Boundary Representation	Memory Storage
SSS: Structured in Lat, Lon, Depth	no	no	very simple implicit point search, very fast	highly constrained (only represents globally planar (or spherical shell) boundaries)	Exceptional: requires storage for model attributes only
SSL: Structured in Lat, Lon; Layered in Depth	no	no	very simple implicit 2D (lat/lon) point search with a 1D separable layer search	functional layer boundaries only (i.e. unable to represent closed contour interior volumes)	Good: requires storage for model attributes and depth profile information
UUL: Unstructured in geographic surface dimensions; Layered in Depth	yes	yes	2D cell walk with a 1D separable Layer search	functional layer boundaries of arbitrary resolution only (i.e. unable to represent closed contour interior volumes)	Memory intensive: requires storage for model attributes, explicit 2D geometry and topology, and depth profile information
UUU: Totally Unstructured	yes	yes	3D cell walk	Fully general	Memory intensive: requires storage for model attributes, explicit 3D geometry and topology, and cell or node based layer identifier

Node:
- Defines a geometrical point in the ***Grid***
- Uses a Cartesian vector representation originating at the Earth's center
  - May be defined as a ***GeoVector*** which defines the point vector as a unit vector with an associated magnitude (radius)
- Contains an optional ***Data*** object which maps model attributes or interpolatory metadata to the nodes position

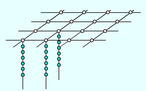


Cell:
- Defines the local physical topology of the grid
- Each cell maintains the nodes from which the cell is constructed and a list of adjacent cells that share common cell faces
- Contains and optional Data object which maps model attributes or interpolatory metadata to the cell



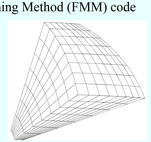
SSS:

- Implicit geographic surface geometry specification (Lat/Lon boundary extent and spacing imply geographic surface node position)
- Layer depth varies at each geographic surface grid position
- Grid Definition contains equally spaced spherical shell profiles defining layer boundaries



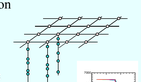
Example

Typical structured grid used in tomography or in De Kools Fast Marching Method (FMM) code



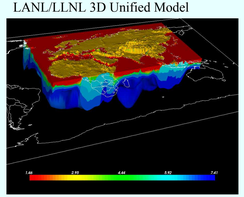
SSL:

- Implicit geographic surface geometry specification (Lat/Lon boundary extent and spacing imply geographic surface node position)
- Layer depth varies at each geographic surface grid position
- Grid Definition contains arbitrary depth profiles at geographic surface grid position
- Typical radial velocity profile



Example

LANL/LLNL 3D Unified Model



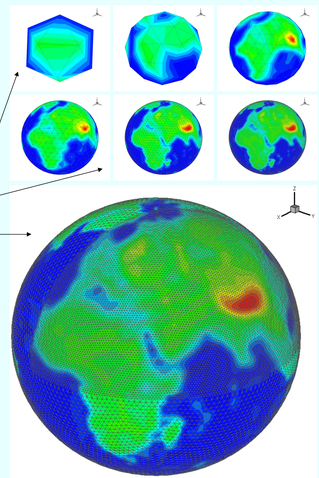
UUL:

- Unstructured geographic surface variation
- Geographic surface grid nodes associated with an array of layer depths

Example

GNEMRE Regional Phase Model (SLBM)

- Uses an unstructured subdivided 2D Tessellation to describe the geographic surface variation.
- Begins with a coarse regular Icosahedron of 20 triangles.
- Each triangle is subdivided into 4 triangles until the desired resolution is attained
- Not necessary to subdivide all triangles
  - Variable resolution is attained by subdividing regions of interest only
  - Transition triangles are used to close triangles subdivided beyond an adjacent neighbor's level
- A radial depth profile is used to define the model velocity similar to that defined for the SSL grid
- Point searching
  - Performed using a triangle walk in the original coarse grid
  - Subdivided child depth search is performed to find the innermost subdivided triangle containing the point
- The Earths surface is modeled as a GRS80 ellipsoid
- Depth profiles from various local or global models are mapped into the ellipsoid



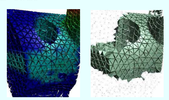
UUU::

- Explicit Geometry Specification (every node position is defined)
- Local Topology Definition (cell and node maintain grid adjacency information)
- The most general grid … any 3D mesh can be represented this way

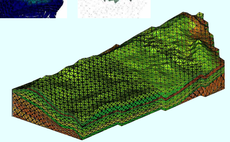
Examples

Unstructured Tetrahedral Grid as illustrated by Menke in his RayTrace3D code

Arbitrary Unstructured Tetrahedral Mesh (as typically used in finite element applications)



Layered hexahedral representation converted to an unstructured tetrahedral grid



Any arbitrary 3D grid generated by 3rd party meshing software (.e.g. The Sandia CUBIT Geometry and Mesh Generation Toolkit)

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.