Postprint: Three-Dimensional Volume Discretization and Encoding of Solar Wind Based on Heliocentric Coordinate System

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Abstract

With the massive growth of space exploration data, higher demands are placed on data visualization and data access efficiency, necessitating effective organization and management of data. This paper addresses the vast Sun-Earth space, combining the characteristics of solar wind data and sampling methods; since meridional resolution is close to latitudinal resolution while radial resolution differs significantly from both, existing three-dimensional volume subdivision models are comparatively analyzed, and the SDOG-R grid is identified as being based on the SDOG grid with further independent subdivision in the radial direction, which not only solves the problem of overly dense grids at the sphere’ s center but also satisfies the requirement that radial resolution be greater than the resolution of the spherical surface in longitude and latitude. Simultaneously, the paper proposes a corresponding encoding scheme for this grid. Experimental verification demonstrates that the solar wind LOD spatial data model based on three-dimensional volume subdivision significantly improves the retrieval and access speed of large-scale massive data.

Full Text

Research on 3D Subdivision and Encoding for Solar Wind Based on Heliocentric Coordinate System

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Abstract

With the exponential growth of space exploration data, higher demands are placed on data visualization and access efficiency, necessitating effective data organization and management. This paper addresses the vast heliocentric spatial volume by analyzing solar wind data characteristics and sampling patterns. Given that meridional and latitudinal resolutions are similar while radial resolution differs significantly, we compare existing 3D volumetric subdivision models. The SDOG-R grid, which performs independent radial subdivision on top of the SDOG grid, not only solves the problem of excessive grid density near the sphere's center but also satisfies the requirement where radial resolution exceeds spherical surface resolution. Additionally, this paper proposes a corresponding encoding scheme for this grid. Experimental validation demonstrates that the LOD spatial data model based on 3D volumetric subdivision significantly improves the retrieval and access speed of massive-scale data.

Keywords: solar wind; spatial subdivision; SDOG-R; encoding

1. Introduction

The development of geographic information systems, particularly digital Earth technologies, has provided powerful means for data organization and management in Earth science research. However, with the rapid advancement of space science and the massive growth of space exploration data, space scientists face urgent challenges in organizing and managing solar system exploration data, as well as improving data visualization effects and access efficiency—issues that hold significant theoretical research value and broad application prospects [1-5].

Since actual solar wind detection data is not yet available, this paper utilizes output data from a 3D solar wind model developed by China' s State Key Laboratory of Space Weather, providing technical support for the organization, management, and analysis of future actual solar wind detection data [6-12].

In the vast solar system space, constructing a 3D volumetric subdivision model is essential to improve retrieval and access speeds for massive solar wind data. This involves generating multi-resolution volumetric data and encoding the grids to achieve efficient organization and access of massive solar wind datasets [13-15].

2.1 Data Characteristics Analysis

The data used in this paper originates from a 3D solar wind model (the Solar Interplanetary Conservation Element and Solution Element (SIP-CESE) 3D solar wind model developed by the SIGMA research group at China' s State Key Laboratory of Space Weather) [1, 14-16]. The data is in polar coordinates with three axes: radius, longitude, and latitude. This solar wind data features irregular sampling characteristics within a Sun-centered spherical sampling space: latitude ranges from -90° to 90° with 55 samples, longitude ranges from 0° to 360° with 80 samples, and radial sampling covers 1 AU with 154 samples.

The sampling intervals are illustrated in [Figure 1: see original paper], [Figure 2: see original paper], and [Figure 3: see original paper]. [Figure 1: see original paper] shows the longitude interval distribution, [Figure 2: see original paper] the latitude interval distribution, and [Figure 3: see original paper] the radius interval distribution. Longitude intervals concentrate around 4.5° with minimal variation, indicating approximately uniform sampling in longitude. Latitude intervals are non-uniform, with larger intervals at low latitudes and smaller intervals at high latitudes, reaching a minimum at the equator. The radius interval distribution reveals that intervals increase linearly with distance from the Sun at a growth rate of approximately 2.86%, with radial sampling frequency far exceeding that in longitudinal and latitudinal directions.

Based on this analysis, solar wind data exhibits similar sampling frequencies in meridional and latitudinal directions (i.e., synchronized meridional and latitudinal resolution), while radial sampling frequency is significantly higher (i.e., radial resolution is not synchronized with spherical surface resolution).

2.2 Comparison and Selection of Subdivision Methods

Current research on volumetric subdivision grids primarily focuses on Earth-space subdivision. To process massive geoscience data, scholars have proposed various global subdivision schemes, including the Yin-Yang grid [16], Stemmer volumetric grid [17], Ballard hierarchical structure [18], Stadler volumetric grid [19], QuaPA [20], Sphere Degenerated-Octree Grid (SDOG) [21], and adaptable SDOG grid [22]. Polyhedron-based subdivision models using tetrahedrons and hexahedrons involve substantial computational overhead and lack generality.

Based on the data characteristics analysis, where longitudinal and latitudinal subdivision levels are similar but radial subdivision differs significantly, the adaptable SDOG-R model emerges as the optimal choice. This model performs recursive binary subdivision along the radial direction on top of the SDOG grid until the radial resolution meets requirements. The model inherits the advantages of spherical degenerated quadtree subdivision while solving the problem of excessive grid density near the sphere’ s center. Independent radial subdivision further satisfies the requirement where radial resolution exceeds spherical surface resolution. Therefore, this paper selects the SDOG-R grid model for 3D volumetric subdivision of solar wind data.

2.3 SDOG-R Grid Model

The SDOG-R grid subdivision process proceeds as follows:

The first subdivision of an octant involves three steps. First, radial division splits the octant along a spherical surface at half the original radius, creating inner and outer grids. Second, longitudinal division takes the midpoints of the two outer meridians on the external surface, connects them with a latitude line, and cuts the outer grid using a conical surface formed by this new latitude line and the sphere’ s center, generating upper and lower outer grids while keeping the inner grid unchanged. Third, latitudinal division takes the midpoints of the upper and lower latitude lines of the lower outer grid and cuts it using a plane defined by these two midpoints and the sphere' s center, creating left and right lower outer grids. These steps are illustrated in [Figure 4: see original paper].

The first octant subdivision produces four sub-grids. Based on their degeneracy characteristics, these are classified as: Sphere Degenerated Grid (SG) for the inner cell, Latitude Degenerated Grid (LG) for the upper outer cell, and Normal Grid (NG) for the left and right lower outer cells. SDOG grids consist entirely of these three basic grid types. The first subdivision yields 1 SG, 1 LG, and 2 NGs.

The second subdivision builds upon the first-layer SDOG grid by subdividing SG, LG, and NG grids respectively. SG follows the rules from step 3. LG grids undergo degenerate subdivision, with both inner and outer layers dividing into 3 blocks each, resulting in 6 blocks per grid. NG grids undergo standard octree subdivision, with each grid dividing into 8 blocks.

On each SDOG grid layer, three additional radial subdivisions are performed to obtain the corresponding SDOG-R grid. Given the original data dimensions of 55×80×154, and since SDOG-R subdivision merges degenerate cells at the sphere' s center and poles from the base SOG (Sphere Octree Grid) grid, the ideal SOG grid dimensions should be $2^m \times 2^n \times 2^p$ where m, n, and p are positive integers. To ensure data completeness, SOG grid dimensions must exceed original data dimensions. An ideal choice uses octant dimensions of $2^7 \times 2^7 \times 2^{10}$, yielding consistent meridional and latitudinal grid density with radial density 8 times greater—i.e., radial resolution exceeds spherical surface resolution. Three radial subdivisions on each SDOG grid layer produce the corresponding SDOG-R grid, as shown in [Figure 5: see original paper].

Each SDOG-R grid layer is generated from its corresponding SDOG grid layer through radial subdivision, with subdivision frequency adjustable based on requirements. When radial subdivision count is zero, the result is a standard SDOG grid.

The subdivision process can be analyzed through radial cross-sections combined with spherical subdivision diagrams, along with grid count calculation methods. [Figure 6: see original paper] illustrates the first SDOG subdivision: radial division splits the octant into 2 layers (inner layer 0 and outer layer 1). The right diagram shows the corresponding spherical grid for outer layer 1, where numbers indicate grid counts—1 for the upper grid and 2 for the lower grids (left and right), totaling 4 grids.

[Figure 7: see original paper] shows the second subdivision: radial division creates 4 layers. The second subdivision essentially compresses the first subdivision' s results into the inner half of the octant, while the outer half represents continued subdivision of the first subdivision' s second layer. This pattern continues, with the third subdivision result shown in [Figure 8: see original paper].

The analysis reveals that grid relative density increases from the outer radius inward, peaking near radius $r/2$, with a secondary peak at $r/4$. When subdivision level is n, radial subdivision yields $2n$ spherical layers.

Excluding the special single grid at the north pole, all other grids relate to powers of 2. The pattern shows that for the i-th subdivision, the outer hemisphere divides into i spherical layers, with the outermost layer grid count given by:

```
12n 0112231135212*22*22*2...2*2222...22(41)3iiiicount       i122*(41)3ii 1311133113312112*(
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When subdivision level exceeds 3, the data compression ratio stabilizes at 61%, saving substantial storage space and grid encoding quantity while effectively balancing excessive polar grid density and homogenizing grid size distribution.

3. SDOG-R Grid Encoding

Grid encoding should follow the principle that adjacent grids have consecutive codes, and consecutive codes correspond to adjacent grids [23]. The Coupled Degenerated Z-curve (CDZ) can address SDOG-R grid encoding [24]. The encoding principle is detailed below using first-subdivision SDOG-R as an example.

First, octants are encoded with octal numbers 0–7 to identify the octant quadrant. Specifically, the northern hemisphere is numbered counterclockwise as 0, 1, 2, 3, and the southern hemisphere as 4, 5, 6, 7, as shown in [Figure 9: see original paper].

Referring to [Figure 5: see original paper], the first octant subdivision splits radially into two layers: inner layer coded as 0 and outer layer as 1. Each layer divides into four grids. The four grids in layer 0 merge into one SG grid coded as 0. The two upper grids in layer 1 merge into one LG grid coded as 4. The lower grids (left and right) become NG grids coded as 6 and 7.

For the second octant subdivision, the top triangular prism encoding follows the same method as the first subdivision unit, dividing into six parts with new grid codes appended by 0, 2, 3, 4, 6, 7. Child hexahedra divide into eight parts with new codes appended by 0–7. Each subdivision level increase adds one encoding digit.

The code after the separator identifies the radial subdivision layer number using binary code. Each SDOG grid undergoes three radial subdivisions (1-to-8 splits). Any SDOG-R grid after subdivision appends radial subdivision identification bits to its original code, separated by a delimiter. More bits represent more subdivisions, with each subdivision adding one digit and producing smaller sub-regions. [Figure 10: see original paper] illustrates radial subdivision after the first SDOG subdivision, while [Figure 11: see original paper] shows the result after three radial subdivisions. The second subdivision follows the same principle, as shown in [Figure 12: see original paper].

A grid is uniquely identified by a code combining the SDOG grid code (before the separator) and the radial layer number (after the separator), expressed as:

$$Morton = q_1 q_2 ... q_n - p_1 p_2 ... p_m$$

where q represents octant quadrant identification bits, "-" is the separator, and p represents radial distinction identification bits after three radial subdivisions on the SDOG grid.

This encoding scheme maps grid data to codes, supporting data retrieval, organization, application, and analysis.

4. Data Organization Example

The original solar wind data, output from the SIP-CESE 3D solar wind model in polar coordinates (latitude, longitude, radius), features irregular sampling: latitude -90° to 90° with 55 samples, longitude 0° to 360° with 80 samples, and radial sampling to 1 AU (149,597,870.691 km) with 154 samples.

Using solar wind particle density data in the heliocentric ecliptic coordinate system, [Figure 13: see original paper] shows the original data visualization. [Figure 14: see original paper], [Figure 15: see original paper], and [Figure 16: see original paper] display SDOG-R subdivided data visualizations at LOD=3, LOD=4, and LOD=5 respectively.

The original data exhibits high density in central regions with increasingly sparse outer data, allowing clear visibility of internal density distributions through gaps. Subdivided data shows more uniform density distribution, causing slightly more occlusion. As LOD values increase, resolution improves with near-real-time loading speeds while completely preserving solar wind characteristics. Original data loading requires over 40 seconds, whereas LOD=4 subdivided data loads in only 3 seconds with smooth zooming and panning operations.

5. Conclusion

This paper addresses massive solar wind volumetric data by analyzing sampling characteristics, revealing similar meridional and latitudinal resolutions but significantly different radial resolution. Uniform subdivision in all three directions would lose radial data features and cause distortion. The SDOG-R grid model effectively solves excessive grid density near the solar center while accommodating asynchronous radial and spherical resolutions, providing multi-resolution data levels and significantly improving retrieval efficiency for irregularly sampled solar wind data.

Future research will focus on implementing non-uniform radial recursive subdivision to better match solar wind data characteristics.

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Note: Figure translations are in progress. See original paper for figures.

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