Postprint: Research on the PDQG-R Subdivision Model and Encoding for Solar Wind Based on Heliocentric Coordinates

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Abstract

With the massive growth of space exploration data, effective organization and management are required to improve data access efficiency and visualization performance. This paper proposes a novel PDQG-R grid model—Planar Degenerate Quadtree Grid—based on existing two-dimensional surface subdivision models, incorporating characteristics of solar wind data, specifically for the ecliptic and meridian planes passing through the solar center of mass. The corresponding grid encoding scheme is also presented. This subdivision model not only resolves the issue of excessive grid density near the solar center, but also accommodates the requirement for asynchronous radial and longitudinal (latitudinal) resolutions, while providing multi-resolution hierarchical data that effectively supports the organization and management of massive spatial datasets.

Full Text

Preamble

Research on PDQG-R Subdivision Model and Encoding for Solar Wind Based on Heliocentric Coordinate System

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Abstract

With the massive growth of space exploration data, effective organization and management are essential to improve data access efficiency and visualization quality. Building upon existing two-dimensional surface subdivision models and considering the characteristics of solar wind data, this paper proposes a novel

PDQG-R grid model—Plane Degenerated Quadtree Grid—for the ecliptic and meridian planes that pass through the solar centroid. A corresponding grid encoding scheme is also presented. This subdivision model not only addresses the problem of excessive grid density near the heliocenter but also accommodates the need for asynchronous radial and longitudinal (latitudinal) resolution while providing multi-resolution hierarchical data, thereby effectively supporting the organization and management of massive spatial datasets.

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

1 Introduction

The development of geographic information systems, particularly digital Earth technologies, has provided powerful tools for data organization and management in Earth science research. In the rapidly advancing field of space science, the massive growth of space exploration data has created an urgent need for space scientists to address how to organize and manage solar system exploration data, and how to improve data access efficiency and visualization effectiveness. This challenge holds significant theoretical research value and broad application prospects [**?**].

As actual solar wind observation data are not yet available, this study utilizes output data from a three-dimensional solar wind model developed by China' s State Key Laboratory of Space Weather, providing technical support for the future organization, management, and analysis of actual solar wind observations [**?**].

In heliocentric space, to investigate how magnetic fields, temperature, and ejected particle density vary with distance from the solar center—and to understand data variation patterns within these planes—it is necessary to construct planar grid subdivision models for two typical cutting planes passing through the solar centroid: the ecliptic plane and the meridian plane. By partitioning data into different resolution levels and encoding the grids, we can achieve efficient data organization across vast circular planes and improve access efficiency for massive datasets [**?**].

2.1 Data Analysis

The data used in this study are outputs from a three-dimensional solar wind model (the Solar-Interplanetary Conservation Element/Solution Element (SIP-CESE) three-dimensional solar wind model developed by the SIGMA research group at China' s State Key Laboratory of Space Weather) [**?**, **?**]. The data are in polar coordinates with three axes: radius, longitude, and latitude. The solar wind data feature irregular sampling: in the 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 extends to 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 of sampling points, [Figure 2: see original paper] shows the latitude interval distribution, and [Figure 3: see original paper] shows the radial interval distribution. The longitude intervals are concentrated 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 radial interval distribution reveals that intervals increase with distance from the Sun, following a linear trend with a slope of approximately 2.86%. Moreover, radial sampling frequency far exceeds that in longitudinal and latitudinal directions.

Based on this analysis, solar wind data exhibit similar sampling counts in longitudinal and latitudinal directions, indicating roughly synchronized resolution in these dimensions. However, radial sampling frequency is significantly higher, resulting in radial resolution that exceeds longitudinal (latitudinal) resolution—i.e., radial resolution is asynchronous with longitudinal (latitudinal) resolution.

For both the ecliptic and meridian planes, the two dimensions have different units: one is distance and the other is angle. Since both planes combine angular and radial coordinates, their essence is identical. This paper uses the ecliptic plane as an example to detail the construction of the subdivision model.

2.2 PDQG-R Subdivision Model

Currently, three typical two-dimensional spatial subdivision models exist: the latitude-longitude subdivision model [?], the polyhedral subdivision model [?], and the Voronoi spherical adaptive grid model [?].

For solar wind subdivision applications, polyhedral and adaptive grid models can be excluded. Polyhedral models involve relatively complex coordinate calculations and differ from existing surveying and remote sensing data organization formats, making integration difficult [?, ?]. Adaptive subdivision models operate at a single scale, making them difficult to combine with multi-resolution approaches [?, ?, ?].

The latitude-longitude subdivision model suffers from severe distortion at the poles, causing excessive grid density near the heliocenter and sparse grids at greater distances. As subdivision levels increase, the size ratio between near and far grids diverges [?].

To enhance grid model adaptability and scalability, this paper introduces the concept of degenerated quadtree [?, ?], combining it with conventional latitude-longitude grids to leverage their respective strengths. This yields a higher-quality grid model called the Plane Degenerated Quadtree Grid (PDQG).

Using the solar ecliptic plane as an example, the PDQG subdivision method proceeds as follows:

1) The ecliptic plane is divided into four quadrants, each a quarter-circle plane spanning 0°–90° in longitude with a radius of approximately 1 AU (the average Earth-Sun distance).
2) Each quarter-circle plane is recursively subdivided using PDQG grids. In the first subdivision, the midpoints of the three edges are identified, yielding three new points. The two new points on the radial edges are connected to form a latitude line. The midpoint of this latitude line is then connected to the remaining new point to form a radial line, creating one new sub-quadrant (approximately triangular) and two sub-quadrilaterals. [Figure 4: see original paper] illustrates this process, where solid lines represent the first subdivision results.
3) The second subdivision recursively divides the two types of sub-grids generated in the first step. Sub-triangles are subdivided using the same method as the first step. For sub-quadrilaterals, conventional quadtree subdivision is applied: midpoints of the four edges are identified, yielding four new points. The midpoints on the two radial edges are connected to the center using concentric arcs, while the midpoints on the two latitude lines are connected directly. This produces four new sub-quadrilaterals, resulting in one new sub-triangle and ten sub-quadrilaterals (2+4+4), achieving higher-resolution subdivision of the quarter-circle plane. In [Figure 4: see original paper], dashed-dotted lines represent the second subdivision.
4) Step 3 is repeated until the desired resolution is achieved. In [Figure 4: see original paper], dashed lines represent the third subdivision results.

A statistical comparison of grid counts after five subdivision levels is presented below:

Comparison of Grid Counts in Quarter-Circle Plane

The relationship can be summarized as follows: when the subdivision level is n, the number of grids generated in a quarter-circle plane satisfies:

For PDQG: The grid count follows a pattern where each level adds terms of the form 2×4^(k-1) for k 2.

For conventional latitude-longitude models, the grid count is 2^(2n+2). This yields a grid compression ratio of approximately 31.3%, 32.8%, 33.2%, and 33.3% for levels 1 through 4, respectively.

When using traditional latitude-longitude subdivision, grid counts grow exponentially at a rate of 2^(2n+2). After degeneration, the count is significantly reduced, saving substantial data storage space and simplifying grid encoding while effectively mitigating excessive grid density near the heliocenter and promoting grid size uniformity.

To address the resolution inconsistency between dimensions—particularly when radial resolution exceeds longitudinal resolution (i.e., radial subdivision levels exceed longitudinal levels)—independent radial subdivision can be applied atop the PDQG grid. This satisfies the requirement for asynchronous radial and longitudinal resolution, leading to the PDQG-R grid model.

Since the quarter-circle data dimensions show radial sampling density is m times the longitudinal density, applying three additional radial subdivisions atop PDQG achieves the required resolution, as illustrated in [Figure 7: see original paper].

[Figure 7: see original paper] shows radial subdivision three times on a specific grid based on three PDQG subdivisions, where solid lines represent the first radial subdivision, dashed-dotted lines the second, and dashed lines the third. Consequently, one PDQG grid becomes eight sub-grids, generating the PDQG-R grid.

Each level of PDQG-R grids is derived from the corresponding PDQG grid level, with the number of radial subdivisions adjustable as needed. When the radial subdivision count is zero, the model reduces to standard PDQG.

3 PDQG-R Grid Encoding

The encoding scheme assigns a unique identifier to each subdivided sub-grid, establishing a one-to-one correspondence between grid coordinates, attribute data, and encoding. For efficient data indexing, the PDQG-R grid encoding rules [**?**, **?**, **?**] are as follows:

1) The ecliptic plane divided into four quadrants is numbered counterclockwise as 0, 1, 2, and 3, establishing each quadrant' s location as shown in [Figure 5: see original paper].

2) After the first subdivision, for each quadrant, the two outer quadrilaterals are numbered counterclockwise as 2 and 3, while the central triangle is encoded as 0 (effectively merging 0 and 1 into 0), as shown in [Figure 6a: see original paper].

3) After the second subdivision, the central triangle encoding follows the same method as the first-level unit. Sub-quadrilaterals are encoded with lower-left and upper-left as 0 and 1, respectively, and lower-right and upper-right as 2 and 3. Each additional subdivision level adds one encoding digit.

4) In the radial direction, each PDQG grid undergoes three radial subdivisions, dividing into eight parts. Any grid can be identified by appending a suffix code to its base encoding to specify its position after radial subdivision. For example, the grid numbered "010" in [Figure 7: see original paper] is one of eight sub-grids generated after PDQG-R subdivision. A separator can be added after the base encoding, with subsequent digits indicating radial subdivision levels using binary codes: one digit for one subdivision, two digits for two subdivisions, with each subdivision adding one digit. More subdivisions produce smaller sub-regions.

In [Figure 7: see original paper], numbering from the center outward uses 0 and 1. The first radial subdivision uses 0 and 1; the second uses 00, 01, 10, and 11; the third uses 000, 001, 010, 011, 100, 101, 110, and 111. The number of encoding digits determines radial subdivision count. The encoding is dynamic, inheritable, and integrates well with multi-resolution hierarchies.

5) Digits after the separator identify radial subdivision levels using binary codes, while other Morton code digits are quaternary numbers not exceeding 3. The Morton code can be expressed as:

$$\text{Morton} = q_0 q_1 \dots q_n - p_1 p_2 \dots p_m$$

where q_0 is the quadrant identifier, "–" is the separator, and $p_1 p_2 \dots p_m$ are radial distinction identifiers after m radial subdivisions atop the PDQG grid.

Through grid encoding, grid data corresponds directly with encoding, supporting data retrieval, organization, application, and analysis.

4 Data Organization Example

The original solar wind data are outputs from the three-dimensional SIP-CESE solar wind model in polar coordinates with three axes: latitude, longitude, and radius. The data feature irregular sampling: latitude ranges from -90° to 90° with 55 samples, longitude ranges from 0° to 360° with 80 samples, and radial sampling extends to approximately 1 AU with 154 samples.

Using solar wind particle density data in the heliocentric ecliptic coordinate system, [Figure 8: see original paper] shows the original absolute density data in the ecliptic plane, while [Figure 9: see original paper] and [Figure 10: see original paper] display subdivided data at LOD=4 and LOD=5, respectively. The original data exhibit high density at the center and sparsity at the periphery, whereas subdivided data become more uniform while completely expressing solar wind characteristics.

Subdivision and encoding effectively organize massive datasets by: (1) providing multi-resolution hierarchical data to improve retrieval speed; (2) better associating spatial positions with attribute data; and (3) reducing redundant data volume to enhance usability.

Conventional latitude-longitude grids suffer from dense meridians at the poles, causing non-convergent grid ratios between poles and equator and severe rendering distortion. To address this, this paper introduces degenerated quadtree subdivision, proposing a novel PDQG grid model for ecliptic and meridian planes based on solar wind data characteristics, along with a corresponding encoding scheme.

This subdivision model effectively resolves excessive grid density near the solar centroid while accommodating asynchronous radial and longitudinal (latitudinal) resolution. It provides multiple resolution levels, significantly improves data retrieval efficiency, and is well-suited for subdividing irregularly sampled solar wind data.

However, the model uses uniform radial intervals. Implementing non-uniform radial recursive subdivision would better align with solar wind data characteristics. While not limited to solar wind data, this model theoretically applies to any data with similar sampling structures. By placing different datasets within the subdivided grids, it enables organization and management of diverse space physics data, demonstrating promising applications for massive space physics data organization.

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