Xingguan boundaries for spatial analysis and cartography in geo-information science

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ABSTRACT

Xingguans, the asterisms in Chinese astronomical culture, constitute a distinct partitioning system that predates and operates on cosmology principles fundamentally different from the astronomical constellations established by the International Astronomical Union (IAU) a century ago. This paper presents methods tailored for geo-information science (GIS) to process, analyze, and visualize the data of Xingguan boundaries, drawing primarily upon the recently promulgated dataset in "Delineating Boundaries of Chinese Xingguans" in ChinaXiv (Zhao, 2026). Using the boundary of star field, Tianshi Yuan (TSY) , as a case study, the paper demonstrates the conversion of right ascension and declination coordinates of spatial positions into spherical polygons interoperable with the World Geodetic System-1984 Coordinate System (WGS84, EPSG:4326). It then formulates the mathematical foundations for area computation, barycenter derivation and spatial indexing and explores the applications of Xingguan boundaries in advanced simulation, numerical computation, GIS data processing and information visualization. The paper therefore explores the integration of Multi-Order Coverage (MOC) maps on HEALPix tessellation for cone and region queries and carries out complexity analyses for spatial indexing operations. In the end it proposes a plug-and-play index that enables seamless integration of Xingguan boundary with existing geo-information databases and data processing platforms. The outcome ascertains that Xingguan boundaries as a modern digital infrastructure are capable of supporting high-resolution data mapping, spheroidal pixelization and culturally informed visualization in geo-information science.

Keywords: Chinese Xingguan boundary, spherical polygon, GIS data processing, Multi-Order Coverage, HEALPix, spatial analysis, GIS cartography, MOC map

1. INTRODUCTION

The Chinese astronomical tradition, spanning more than three millennia, has developed one of the most elaborate and enduring Xingguan system of celestial nomenclature and classification in human civilization. Unlike the IAU constellation system, which partitions the celestial sphere into 88 sky regions of polygonal shape, the Xingguan system is organized around named asterisms with cultural, bureaucratic, and cosmological significance in a three-tier hierarchy: (i) six top-level star regions, two polar regions and four zodiac quadrant regions symbolized by the four auspicious motifs, (ii) thirty-two middle-level star fields encompassing the three enclosures, plus the twenty-eight mansions and the near-south-pole star field and (iii) 321 bottom-level individual star areas, each encompassing a unique asterism. The recent boundary delineation for the hierarchy by Zhao[1] has, for the first time, produced a complete and unambiguous partitioning of the celestial sphere in 359 boundary segments that seamlessly assign every point on the sky to a specific Xingguan constituency. This development opens a new avenue of research for geographic information science (GIS). The delineated boundaries are fundamentally spatial data: they are defined as linear-rectangular spherical polygons delineated along lines of constant right ascension (RA) and declination (Dec), forming chains of orthogonal vertices (turns) on the celestial sphere[1][2]. The polygons exhibit such properties as polygonal topology, hierarchical nesting and spatial indexing, which are both familiar to spatial information scientists and uniquely challenging in that: (a) their spherical geometry demands computation of non-Euclidean areas, (b) their boundary data is naturally expressed in the International Celestial Reference System (ICRS) J2000.0 rather than terrestrial coordinate systems and (c) their cultural semantics of the indigenous astronomical tradition impose constraints on visualization and query,neither having terrestrial analogue.

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Hence, this paper addresses three objectives. First, it presents a complete GIS data processing workflow for representing the data of Xingguan boundaries with angular coordinates that are interoperable with geographic coordinate systems, using the boundary of star field TSY as a worked example. Next, it develops formal mathematical operations of spatial analysis on Xingguan boundaries, including computation of spherical polygon areas, barycenter determination, MOC-based masking and querying, complexity analysis and plug-and-play indexing. Finally, it demonstrates the application of these methods in advanced simulation, numerical computation, spatial information and data visualization to establish the Xingguan boundaries as a practical resource for both GIS research and astronomical cultural heritage preservation.

It is necessary to point out that Xingguan boundaries in this paper are exploited as a spatial dataset interoperable with WGS84, EPSG:4326. The GIS data and methods applied in this paper also operates on the sphere with angular coordinates in the ICRS frame. The work for implementation and validation testing of the methods is represented in Figure 1 and Table 1.

2. DATA AND METHODS

2.1 Structures of Boundary Data

The dataset of Xingguan boundaries consists of 359 boundary segments, each encoded as a sequence of vertices in ICRS J2000.0 coordinates (RA, Dec)[1]. Figure 1 shows the Plate Carrée projection of full sky map of the boundaries of 32 star fields, with star field TSY being highlighted in blue. Figure 2 shows the boundary of the star field TSY which, within the Xingguan system, encloses 19 Xinguans, the boundary data comprises the coordinates of 36 vertices, forming a complex multi-segmental polygon that spans approximately 70.5 degrees in longitude (or 4.7 hours in right accession) and 55.25 degrees in latitude (or declination). Each vertex is annotated with a serial number and a turn of direction, SE, ES, SW, WS, WN, NE, or EN, indicating the orientation of the boundary segment at that vertex. In astronomy, the vertex coordinate is presented in form of hour angle (hh:mm:ss) for right accession (RA) and degrees-minutes-seconds (dd:mm:ss) for declination (Dec).

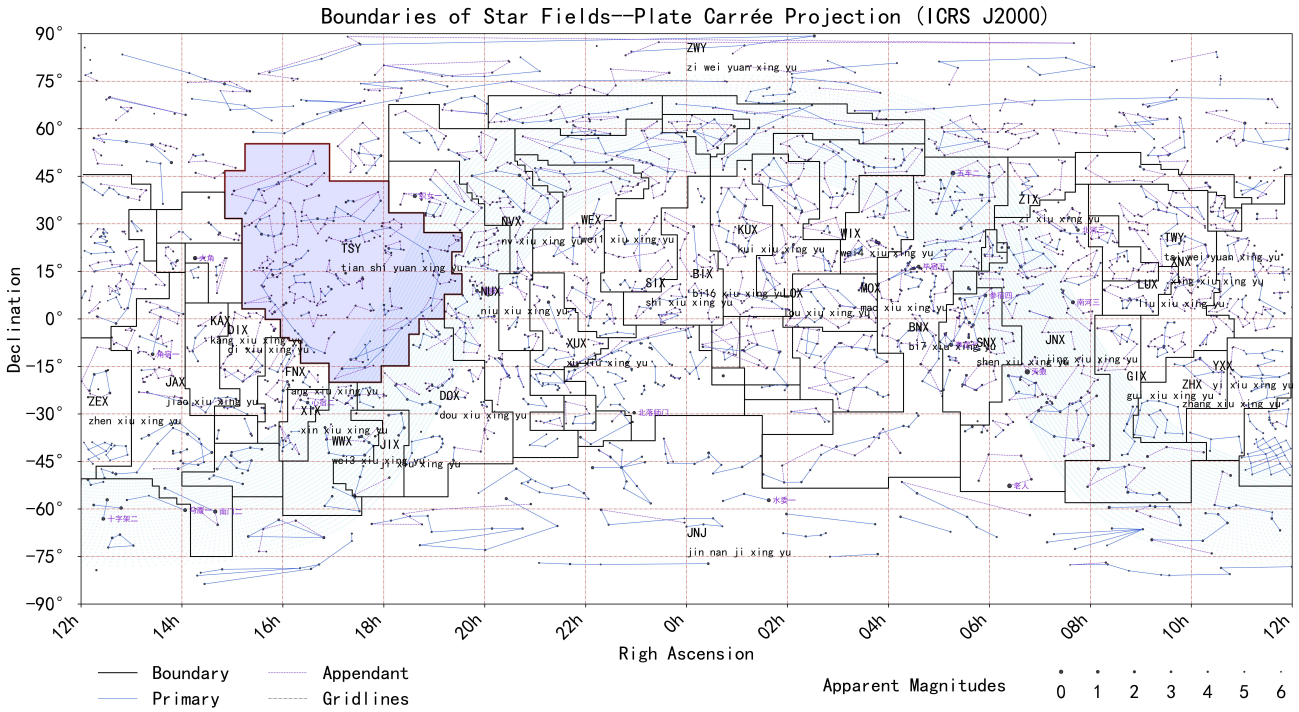


Figure 1. Full sky map in Plate Carrée projection (ICRS J2000) for the boundaries of 32 star fields in the intermediate layer of the Chinese Xingguan hierarchy.The top layer (6 star regions) and bottom layer (321 star areas) are not plotted, but they are shown in Figures 8 and 12 of Zhao[1].

The acronym, TSY, also designates a code from the labeling scheme (see Figure 13 in Zhao [1]), while the annotations of the labels of turns encode the orthogonal direction changes at every vertex: the capital letters S, E, W and N refer to South,

East, West and North, respectively, and the two-letter codes after the vertex serial number indicate the incoming and outgoing directions, respectively. This encoding is designed for delineating Xingguan boundaries and it also facilitates the boundary indexing algorithm pioneered by Nancy Grace Roman in 1987[3], which stores boundary crossings along declination strips to enables efficient positional queries.

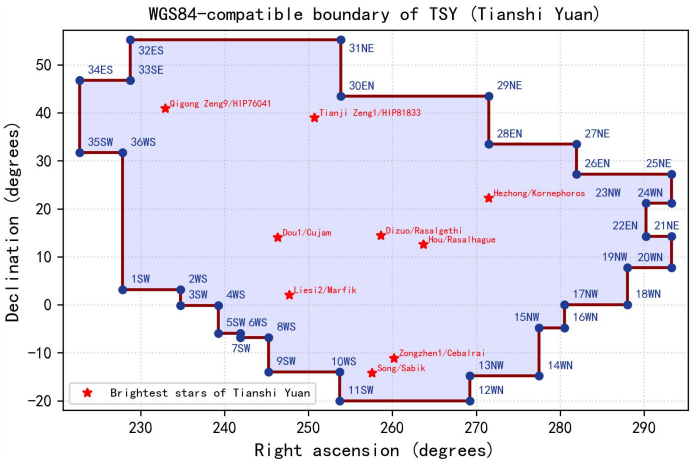


Figure 2. Boundary of TSY plotted with 36 vertices with WGS84 compatible coordinates, the vertices stepping and turning anti-clockwise along right accessions or longitudes and declinations or latitudes (in terms of astronomy, the vertices are delineated clockwise along parallels and meridians of the celestial sphere).

2.2 Coordinate Conversion

The ICRS J2000.0 coordinates, as shown in Table 1, is interoperable with WGS84 (EPSG:4326) and their formation involves two algorithmic steps. First, the spherical coordinates must be expressed in a standard format. For a vertex at RA = α (in degrees) and Dec = δ (in degrees), the Cartesian coordinates on the unit sphere are:

$$x = \cos\delta\cos\alpha, \quad y = \cos\delta\sin\alpha, \quad z = \sin\delta \tag{1}$$

For the boundary of star field TSY, the first vertex at RA = 15:11:26.432, Dec = +03:09:00.000 yields α=227.8601330°, δ=3.15000°, and thus x=−0.669929, y=−0.740389, z=0.054950.

Table 1. Coordinates of TSY boundaries in ICRS J2000.0, compatible with WGS84 (EPSG:4326) angular coordinates for celestial GIS storage

No	RA (h:m:s)	Dec (d:m:s)	RA (deg)	Dec (deg)	Turn	No	RA (h:m:s)	Dec (d:m:s)	RA (deg)	Dec (deg)	Turn
1	15:11:26.432	+03:09:00.000	227.860133	3.150000	SW	19	19:12:00.000	+07:45:54.000	288.000000	7.765000	NW
2	15:39:00.000	+03:09:00.000	234.750000	3.150000	WS	20	19:33:00.000	+07:45:54.000	293.250000	7.765000	WN
3	15:39:00.000	-00:09:00.000	234.750000	-0.150000	SW	21	19:33:00.000	+14:15:00.000	293.250000	14.250000	NE
4	15:57:00.000	-00:09:00.000	239.250000	-0.150000	WS	22	19:21:00.000	+14:15:00.000	290.250000	14.250000	EN
5	15:57:00.000	-05:57:00.000	239.250000	-5.950000	SW	23	19:21:00.000	+21:09:00.000	290.250000	21.150000	NW
6	16:07:30.000	-05:57:00.000	241.875000	-5.950000	WS	24	19:33:00.000	+21:09:00.000	293.250000	21.150000	WN
7	16:07:30.000	-06:51:00.000	241.875000	-6.850000	SW	25	19:33:00.000	+27:15:00.000	293.250000	27.250000	NE
8	16:21:00.000	-06:51:00.000	245.250000	-6.850000	WS	26	18:47:42.000	+27:15:00.000	281.925000	27.250000	EN
9	16:21:00.000	-14:00:00.000	245.250000	-14.000000	SW	27	18:47:42.000	+33:27:00.000	281.925000	33.450000	NE
10	16:54:52.200	-14:00:00.000	253.717500	-14.000000	WS	28	18:06:00.000	+33:27:00.000	271.500000	33.450000	EN
11	16:54:52.200	-20:00:00.000	253.717500	-20.000000	SW	29	18:06:00.000	+43:30:00.000	271.500000	43.500000	NE
12	17:57:00.000	-20:00:00.000	269.250000	-20.000000	WN	30	16:55:30.000	+43:30:00.000	253.875000	43.500000	EN
13	17:57:00.000	-14:49:30.000	269.250000	-14.825000	NW	31	16:55:30.000	+55:15:00.000	253.875000	55.250000	NE
14	18:30:00.000	-14:49:30.000	277.500000	-14.825000	WN	32	15:15:00.000	+55:15:00.000	228.750000	55.250000	ES
15	18:30:00.000	-04:49:30.000	277.500000	-4.825000	NW	33	15:15:00.000	+46:45:00.000	228.750000	46.750000	SE
16	18:42:00.000	-04:49:30.000	280.500000	-4.825000	WN	34	14:51:00.000	+46:45:00.000	222.750000	46.750000	ES
17	18:42:00.000	+00:00:00.000	280.500000	0.000000	NW	35	14:51:00.000	+31:41:06.000	222.750000	31.685000	SW
18	19:12:00.000	+00:00:00.000	288.000000	0.000000	WN	36	15:11:26.432	+31:41:06.000	227.860133	31.685000	WS

Second, compatibility with WGS84 for celestial coordinates is nominal in the sense that WGS84 is a terrestrial reference system; the appropriate celestial reference system is the ICRS frame, which is the fundamental reference frame for modern

astronomy. However, for interoperability with spatial data infrastructures, the data of Xingguan boundaries can be stored as geometry in a spatial database with the ICRS frame declared or converted to geocentric Cartesian coordinates (EPSG:4978) for visualization. The conversion between ICRS and WGS84 Cartesian coordinates involves the frame bias and precession-nutation transformation matrices, but for the purpose of boundary representation, the angular coordinates (RA, Dec) are preserved exactly when the reference frame is used.

2.3 Spherical Polygon Representation

Each Xingguan boundary defines a spherical polygon whose edges are segments of either great circles (for declination boundaries) or small circles (for RA boundaries, which are meridians and hence great circles; the RA boundaries are great circles only if they pass through the poles, which they do not for Xingguan system). A spherical polygon is formally defined by an ordered sequence of vertices $(\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_n)$ on the unit sphere, with edges being the geodesic arcs connecting consecutive vertices.

For the boundary of TSY, the polygon is not convex and its interior is defined by the boundary traversal rule: the interior is always to the left of the direction of travel (when viewed from outside the sphere), consistent with the turn encoding. The spherical excess E of the polygon is computed as:

$$E=\sum_{i=1}^{n}\theta_i-(n-2)\pi \tag{2}$$

where θ_i are the interior angles at each vertex, computed from the tangent vectors of the incoming and outgoing edges. The area of the spherical polygon is then computed as follows:

$$A = E \cdot R^2 \tag{3}$$

where R is the radius of the sphere (for the celestial sphere, R=1 and area is expressed in steradians or square radians)[4]. For the boundary of TSY, direct computation of the area using the spherical excess formula yields a value that can be cross-validated against the parametric computations provided in Zhao[1].

3. DATA PROCESSING AND SPATIAL ANALYSIS

3.1 Mathematical Description of Boundary Operations

The data structure of TSY boundary admits a clean mathematical formulation for celestial GIS operations. Let P be the spherical polygon representing a Xingguan boundary, defined by its vertex sequence $\boldsymbol{V}=\{\boldsymbol{v}_1,\ldots,\boldsymbol{v}_n\}$. The point-in-polygon test for a query point $\boldsymbol{q}$ on the sphere is performed by counting the number of boundary crossings along a geodesic arc from $\boldsymbol{q}$ to a reference point (typically the north celestial pole):

$$N(\mathbf{q})=\sum_{i=1}^{n}1\left[arc(\boldsymbol{q},\boldsymbol{p})\cap e_i\neq\varnothing\right] \tag{4}$$

where e_i is the ith edge of P and $arc(\boldsymbol{q}, \boldsymbol{p})$ is the geodesic from $\boldsymbol{q}$ to the pole. The point is inside if $N(\boldsymbol{q})$ is odd. For the orthogonal boundaries of Xingguan polygons, this computation is simplified considerably because the edges are either RA-constant or Dec-constant segments, allowing the crossing test to reduce to a comparison of angular intervals.

3.2 Computation of Barycenters of Boundaries

The barycenter, i.e. center of mass, of a spherical polygon P with uniform surface density is:

$$\mathbf{c}=\frac{1}{A}\int_P \mathbf{r}\ dA \tag{5}$$

where dA is the area element on the unit sphere. Using the divergence theorem on the sphere, this integral can be reduced to a line integral along the boundary:

$$\mathbf{c}=\frac{1}{2A}\oint_{\partial P}\mathbf{r}\times d\mathbf{r} \tag{6}$$

For a polygonal boundary with geodesic edges, this line integral can be evaluated analytically edge by edge. For the TSY polygon as shown in Figure 2, the barycenter computed via this method yields a position that can be compared with the central star positions of all the asterisms inside the star field TSY. The barycenter provides a natural representative point for the star fields in the Xingguan system, useful for spatial indexing and cartographic labeling, as illustrated in Figure 1.

3.3 Multi-Order Coverage (MOC) Masking and Queries

The integration of Xingguan boundaries with the Multi-Order Coverage (MOC) standard of the International Virtual Observatory Alliance (IVOA) provides a mechanism for spatial queries and masking[5][8]. A MOC is a hierarchical encoding of starry sky using the HEALPix[6][7] tessellation, in which each cell (in fact pixel of HEALPix) is identified by a level (order) of the spheroidal pixelization hierarchy and a pixel index. For the polygon of a Xingguan boundary P, the MOC mapping is constructed by identifying all HEALPix cells at a given maximum order $k_{\max}$ that are fully contained within P:

$$\mathcal{M}(P,k_{\max}) = \bigcup_{j=0}^{k_{\max}} \{cell(j, ipix) \mid cell \subseteq P\} \tag{7}$$

The MOC of the boundary of TYS star field at order 12 (corresponding to cells of approximately 0.86 arcminutes) contains on the order of 10^7cells, given the boundary area of 4.656609 square degrees or 0.8127315 steradians.

Cone search. A cone search query with center (α_0,δ_0) and radius ρ returns all datasets whose MOC intersects the cone. The intersection test between a MOC cell and a cone is performed in the HEALPix angular coordinate system:

$$intersect(cell,cone) \Longleftrightarrow d_{ang}(cell_center,(\alpha_0,\delta_0)) \le \rho + r_{cell} \tag{8}$$

where r_{cell} is the maximum angular radius of the HEALPix cell at its order. For the MOC server at Strasbourg Astronomical Data Center (CDS), it shows that cone searches with radii of a few arcminutes over the full MOC database (41,688 datasets as of 2024) achieve response times of a few seconds. For Xingguan-specific queries, it is expected that the cone search can be restricted to the MOC of the target Xingguan, reducing the candidate set by several orders of magnitude.

Region search. Given a sky Region Of Interest (ROI) defined as another spherical polygon Q, (here region refers to any star region, star field or star area) the region search returns all Xingguan boundaries that intersect Q. In MOC terms, this is the intersection operation:

$$\mathcal{M}(P) \cap \mathcal{M}(Q) \neq \varnothing \tag{9}$$

MOC intersection, union, and difference operations are performed on the hierarchical cell lists, with computational complexity proportional to the number of cells in the coarser MOC. For a region search involving the TSY boundary and a rectangular ROI covering the star field TSY, the MOC intersection identifies the relevant boundary cells in milliseconds.

3.4 Complexity Analysis and Spatial Indexing

The performance of spatial queries on Xingguan boundaries depends critically on the indexing strategy. For a brutal linear scan over n boundary vertices, the point-in-polygon test has time complexity $O(n)$. For the TSY polygon with n=36 vertices, this is negligible. However, for queries involving all 321 Xingguans (total vertex count on the order of 10^4), the complexity becomes significant. The Roman[3] table indexing scheme, adapted in Zhao[1], organizes boundaries by declination strips. For a query at declination δ_q, only boundaries that cross the strip containing δ_q need to be examined. If boundaries are distributed uniformly in declination, the expected number of candidate boundaries is $O(N_{total}/N_{strips})$, and the point-in-polygon test becomes $O(n/N_{strips})$ per boundary. For N_{strips}=1800 (1 arcminute strips), this represents a reduction of over three orders of magnitude. A more sophisticated approach uses a two-level index combining HEALPix and R-tree structures. The HEALPix level partitions the sky into 12×4^k cells at order k, providing global localization, while the R-tree level within each cell provides fine-grained local queries. The expected query complexity for this hybrid index is:

$$T_{query}(n) = O\left(\frac{n}{12\times 4^k} + \log n_{cell}\right) \tag{10}$$

where n_{cell} is the number of objects in the target HEALPix cell. For the Xingguan dataset with $n \approx 10^4$ vertices and k=8 (approximately 0.9 arcminute cells), the first term is negligible and the query time is dominated by the R-tree logarithmic term.

3.5 Plug-and-Play Indexing

The boundary data format designed by Zhao[1][9] is initially intended for straight integration into existing astronomical databases, its is also interoperable with GIS platforms. The Flexible Image Transport System (FITS) standard format of the boundary data enables import into any FITS-compatible tool, while the vertex-turn encoding allows boundary reconstruction without external metadata. For database integration into MySQL 5.1+, for instance, as implemented in the

HTM and HEALPix indexing plug-ins, the arrangement enables the spatial indexing table of Xingguan boundary transparent to the workflow. The index is created automatically when the table is registered and all spatial queries are written to use the index without user intervention:

```
SELECT asterism_name FROM xingguan_boundaries
WHERE MOC_Intersects(MOC_Column, MOC_QueryRegion) = 1
```

This plug-and-play capability means that Xingguan boundaries can be added to existing astronomical archives (SIMBAD[10], VizieR[11] NED) with minimal infrastructure changes, immediately enabling culturally informed spatial queries.

4. APPLICATIONS

4.1 Advanced Simulation

The Xingguan boundaries enable high-fidelity simulation of celestial observations for the *de facto* cultural astronomy and heritage preservation. Consider a simulated observation of the TSY star field with a telescope having a circular field of view of radius ρ. The set of Xingguans observable in this field is:

$$S(\alpha_0,\delta_0,\rho) = \{P \mid \mathcal{M}(P) \cap C(\alpha_0,\delta_0,\rho) \neq \varnothing\} \tag{11}$$

where C is the conical field of view. For a simulation covering the entire sky at a given limiting magnitude, the Xingguan MOC mapping can be used as a mask to partition the sky into Xingguan-specific observation plans. The three-tier hierarchy (six star regions, 32 star fields and 321 star areas) provides multiple levels of resolutions for simulation design as such that coarse simulations can use the six-region partition, while high-resolution simulations can resolve individual Xingguan boundaries. For example, to simulate the visibility of Xingguan named Guansuo, labelled as GSu, from a given observatory site and time, the barycenter of GSu, computed via Equation (6), determines its local sidereal time of transit and the MOC mapping, as expressed via Equation (7), enables computation of which portions of the star area are above the horizon at any given moment, using the horizon mask operation:

$$\mathcal{M}_{visible}(t) = \mathcal{M}(P) \cap \mathcal{M}_{horizon}(t, \phi_{obs}) \tag{12}$$

where ϕ_{obs} is the observatory latitude and t is the time.

4.2 Numerical Computation

The dataset of Xingguan boundaries supports a range of numerical computations that are useful for astronomical research and education. The star area of each Xingguan, computed via Equation (3), provides a quantitative measure of the angular extent of the star area. For Xingguan GSu, the area in square degrees can be cross-validated against the parametric computations provided by Zhao[1]. The ranking ratio of the star area, i.e. the ratio of an star area to the total area of the celestial sky covered by the Xingguan system, gives a measure of relative prominence in the Chinese celestial taxonomy.

The barycenter computation via Equation (6) enables numerical studies of centroidal statistics for Xingguan system. For the 321 Xingguans, the distribution of barycentric positions in Galactic coordinates reveals the cultural bias of the Chinese system: whether or not Xingguans are preferentially placed in certain Galactic latitudes or longitudes. Such analyses are enabled by the numerical algorithms presented in Section 3 and it is expected that the results contribute to the quantitative study of Chinese astronomical heritage.

4.3 Geo-information MOC Method

The Xingguan boundaries constitute a unique celestial spatial dataset that can be dealt with by GIS methods, i.e., spherical polygons, spatial indexing, MOC queries and masking, without being in terrestrial GIS layers. The spherical polygons allow Xingguan boundaries to be stored, queried and visualized alongside terrestrial data in any GIS platform that supports spherical geometry. The MOC-enabled query mechanism (see Section 3.3) provides interoperability with the Virtual Observatory infrastructure, enabling cross-matching between Xingguans and astronomical catalogues. A practical celestial GIS application is the generation of Xingguan-specific sky maps, using the MOC of a given Xingguan as a mask, an all-sky image or catalog can be filtered to show only sources within the specific Xingguan. The mask operation:

$$image_{asterism} = image_{all-sky} \otimes \mathcal{M}(P) \tag{13}$$

where $\otimes$ denotes the pixel-wise application of the MOC mask, enabling generation of customized sky maps for any of the 321 Xinguans. This capability is necessary for both research (e.g., studying the stellar content of specific Xingguans) and education (e.g., generating culturally contextualized star charts).

4.4 Visualization of GIS Information

The three-tier hierarchical structure of the Xingguan system lends itself naturally to multi-resolution visualization of celestial GIS information. At the coarsest level, the six star regions provide a high-level partition of the sky. At the intermediate level, the 32 star fields reveal the Three Enclosures and Twenty-Eight Mansions structure. At the finest level, the 321 individual star areas provide the full cultural resolution of the Chinese celestial taxonomy.

The boundary data supports visualization in multiple map projections. The Plate Carrée (equirectangular) projection as shown in Figure 1 is particularly suitable for the orthogonal RA-Dec coordinates of polygons for Xingguan boundaries, because the boundaries appear as horizontal and vertical lines in this projection, preserving the visual character of the traditional Chinese star maps. The MOC-based mapping additionally supports visualization on any HEALPix-compatible platform, including three-dimensional (3D) celestial globes and immersive virtual reality environments. For example, the boundary of star field TSY can be rendered as a colored polygon on a celestial sphere with the constituent stars of the asterisms highlighted at their catalogued positions. The turn codes (SE, ES, SW or WS.) at each vertex can be visualized as direction arrows, providing an intuitive signs of the boundary topology. In combination with the MOC mask, the boundary can be highlighted against the background of the full-sky map (as in Figure 1).

5. CONCLUSION

This paper presents a comprehensive celestial, rather than terrestrial, GIS framework for processing, analyzing, and visualizing the boundary data of Chinese Xingguans, using the star field TSY as a representative case study. The key contributions are threefold. First, it formalizes the coordinate conversion and spherical polygon representation of Xingguan boundaries, providing the mathematical foundations for all subsequent operations. Second, it develops the spatial analysis methods for Xingguan boundaries, including spherical polygon area and barycenter computation, MOC-based cone and region queries, complexity analysis for spatial indexing and plug-and-play database integration. Third, it demonstrates the application of these methods across four domains, i.e. simulation, numerical computation, celestial GIS and visualization, establishing Xingguan boundaries as a modern digital infrastructure for culturally informed celestial GIS research.

The dataset of Xingguan boundaries, with its 359 boundary segments in three-tier hierarchy, represents a significant advance in the digital preservation and computational accessibility of Chinese astronomical heritage. The methods presented here provide a template for the integration of this culturally significant dataset into a broader ecosystem of astronomical data science and celestial geo-information science. Future work will explore the extension of these techniques to the development of interactive visualization tools for public engagement and the integration of Xingguan boundaries with time-domain workflows in both astronomy and spatial geo-information workflows.

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