Research in Astronomy and Astrophysics, 24:015008 (9pp), 2024 January https://doi.org/10.1088/1674-4527/ad08e8

A Cross-matching Service for Data Center of Xinjiang Astronomical Observatory

Hai-Long Zhang[1,2,3], Jie Wang[1,3], Xin-Chen Ye[1,3], Wan-Qiong Wang[1], Jia Li[1], Ya-Zhou Zhang[1,4], Xu Du[1,4], Han Wu[1,4], and Ting Zhang[1,4]

[1] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China; zhanghailong@xao.ac.cn, wangjie@xao.ac.cn
[2] Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China
[3] National Astronomical Data Center, Beijing 100101, China
[4] University of Chinese Academy of Sciences, Beijing 100049, China
Received 2023 June 21; revised 2023 October 12; accepted 2023 November 1; published 2023 December 13

Abstract

Cross-matching is a key technique to achieve fusion of multi-band astronomical catalogs. Due to different equipment such as various astronomical telescopes, the existence of measurement errors, and proper motions of the celestial bodies, the same celestial object will have different positions in different catalogs, making it difficult to integrate multi-band or full-band astronomical data. In this study, we propose an online cross-matching method based on pseudo-spherical indexing techniques and develop a service combining with high performance computing system (Taurus) to improve cross-matching efficiency, which is designed for the Data Center of Xinjiang Astronomical Observatory. Specifically, we use Quad Tree Cube to divide the spherical blocks of the celestial object and map the 2D space composed of R.A. and decl. to 1D space and achieve correspondence between real celestial objects and spherical patches. Finally, we verify the performance of the service using Gaia 3 and PPMXL catalogs. Meanwhile, we send the matching results to VO tools-Topcat and Aladin respectively to get visual results. The experimental results show that the service effectively solves the speed bottleneck problem of cross-matching caused by frequent I/O, and significantly improves the retrieval and matching speed of massive astronomical data.

Key words: virtual observatory tools – astronomical databases: miscellaneous – catalogs

1. Introduction

The cross-matching calculation is the basis for the fusion of multi-band astronomical observations and a key technique for multi-band astronomy research. It can realize the fusion of astronomical data from different bands to obtain multi-band or all-band data, which is beneficial for astronomers to reveal celestial information and better use the various data in the catalog for scientific research (Yu et al. 2019). With the rapid development of astronomical technology, many countries have built or plan to build telescopes covering multiple bands. For instance, (i) in the radio band, Square Kilometre Array (Dewdney 2008), Five-hundred-meter Aperture Spherical radio Telescope (Nan et al. 2011), Robert C. Byrd Green Bank Telescope (Prestage et al. 2009), and the upcoming QTT (QiTai radio Telescope) under construction (Wang et al. 2023; Zhang et al. 2023a), etc. (ii) in optical band, European Extremely Large Telescope (Gilmozzi & Spyromilio 2007), Large Synoptic Survey Telescope (Zhan & Tyson 2018), Large sky Area Multi-Object fiber Spectroscopic Telescope (Cui et al. 2012), etc. (iii) in other band, Lunar-based Ultraviolet Telescope (Wang et al. 2015), Cherenkov Telescope Array (Acharya et al. 2017), extended ROentgen Survey with an Imaging Telescope Array (Predehl et al. 2021), etc. It can be seen that astronomy has entered the big data and full-band era (Cui et al. 2020), and the measurement errors of various astronomical telescopes have led to different data obtained from observing the same celestial object, causing some difficulties in integrating multi-band or full-band astronomical data.

The Data Center of Xinjiang Astronomical Observatory (XAO-DC) was built in 2015 (Zhang et al. 2022), the main data sources include Nanshan 26 m Radio Telescope (NSRT; Xu et al. 2018) and Nanshan One meter Wide-field Telescope (NOWT; Bai et al. 2020). It provides online retrieval services for pulsar, molecular spectrum, active galactic nuclei, and NOWT data sets (Zhang et al. 2019). In order to facilitate astronomers to better use the data in the astronomical catalogs for scientific research, we develop a cross-matching service for XAO-DC.

The service features that we developed can be summarized as follows:

(i) We implement pseudo-spherical sky partition, which divides the whole sky sphere into $\sim 6 \times 4^{30}$ approximately equal blocks to accurately locate the required data and reduce unnecessary data reading, thereby reducing disk I/O.

(ii) The service improves the speed of cross-matching by using pseudo-sphere index technology and parallel computing technology, so that the time consumption of astronomical catalogs cross-matching of tera-scale is less.
(iii) Experimental results show that our online cross-matching service achieves 4 trillion cross-matching computation results in less than one second.

The rest of this paper is organized as follows. In Section 2, some related works about cross-matching calculation are introduced. The developed cross-matching service, which is the core of this paper, is presented in detail in Section 3. In Section 4, real astronomical catalogs are tested and the experimental results are verified. Finally, Section 5 concludes the paper.

2. Related Work and Background

2.1. Related Work

The astronomical catalogs contain a variety of celestial parameters, collecting data obtained by the telescope during a specific period of astrometry. Nowadays, computer experts in many countries are studying the method of astronomical catalogs cross-matching, and have developed some tools or algorithms. Budavari & Szalay (2007) have nicely formulated cross-matching in a Bayesian framework for improving the speed, and it is a solid theoretical foundation and improving recall and precision. Pineau et al. (2011) have developed an efficient and scalable cross-matching service for (very) large catalogs, and it supported customized cross-matching operations. VizieR (Ochsenbein et al. 2000) designed by the Centre de Données de Strasbourg (CDS), includes the cross-matching of astronomical observations and large catalogs, which can be performed by uploading directory files and astronomical catalogs in the tool. SIMBAD (Wenger et al. 2000) provides multi-source query for small files of astronomical catalogs, which is based on cross-matching of small astronomical catalogs. Many different options can be selected during cross-matching, such as the type of source. Xmatch (Budavari & Lee 2013) is one of a wide range of cross-matching tools, which integrates data sets of many observatories, such as 2MASS, GSC, GALEX, UCAC, WISE, etc. It can provide many functions such as download, query and integration of astronomical tables. ARCHES (Motch et al. 2016) is a cross-matching service for high-energy astrophysics research, which provides multi-band data with complete characteristics in the form of spectral energy distribution. Astronomers can submit their own retrieval script through HTTP API, and the system will send astronomers the results of cross-matching after the script is run. catsHTM (Soumagnac & Ofek 2018) uses HTM index to store hierarchical astronomical catalogs in HDF5 files, integrates DECaLS/DR5, FIRST, Gaia/DR1, Gaia/DR2, GALEX/DR6Plus7 and other data sets, and it can support cross-matching between dozens of astronomical catalogs.

To speed up cross-matching calculation, Pei et al. (2011) greatly improved the speed of cross-matching using Python multi-core parallel method. Zhao et al. (2009) used HEALPix to divide the astronomical catalogs, combined with the bit operation fast index, and controlled the cross-matching time of large-scale astronomical catalogs within 32 minutes. Du et al. (2014) combined two partition indexing methods, HTM and HEALPix, and used thread pool technology to accelerate the cross-matching time. They reduced the cross-matching time of large-scale astronomical catalogs to 23 minutes, and controlled the cross-matching time of medium-sized astronomical catalogs to 7 minutes. Ma et al. (2018) proposed E-Zone algorithm, which uses Euclidean distance for faster calculation of adjacent points, and implements parallel calculation based on OpenMP. Li et al. (2019) designed a multi-band catalog unified format, combined with the data layout strategy of minimum conflict to improve the parallelization of cross-matching, and achieved 30.3% and 30.7% time reduction compared with Quad Tree Cube (Q3C) and HealpiX-tree-C (H3C) at 200 million data sources of astronomical catalogs. Zhang et al. (2023b) proposed a large-scale cross-matching framework supporting heterogeneous computing, which reduced the cross-matching time to 5 s for small-scale astronomical catalogs, 150 s for medium-scale astronomical catalogs, and 260 s for large-scale astronomical catalogs.

2.2. The Cross-matching Based on Celestial Coordinates

The cross-matching calculation of astronomical catalogs can combine various information, such as location, density, luminosity, wavelength, and so on. We choose to combine with celestial coordinates because catalogs obtained by different telescopes all contain information about the location of celestial sources. Therefore, we can determine whether two catalogs are homologous or non-homologous by comparing the information of celestial coordinates. As shown in Figure 1, the two points A and B come from astronomical catalogs A and B, respectively. When the spherical distance $d \leqslant 3\sqrt{r_1^2 + r_2^2}$ (in theory), where r_1 and r_2 are the error radius of the two catalogs, the two points are successfully matched as the same object. When implemented on the web side, we provide *Search radius* options, users can enter matching radius according to actual needs, the output condition is that the distance between two points in the input catalog and the matching catalog is less than *Search radius*.

3. A Cross-matching Service for XAO-DC

3.1. The Overall Design of the Service

We develop an online cross-matching service based on the German Astrophysical Virtual Observatory DaCHS

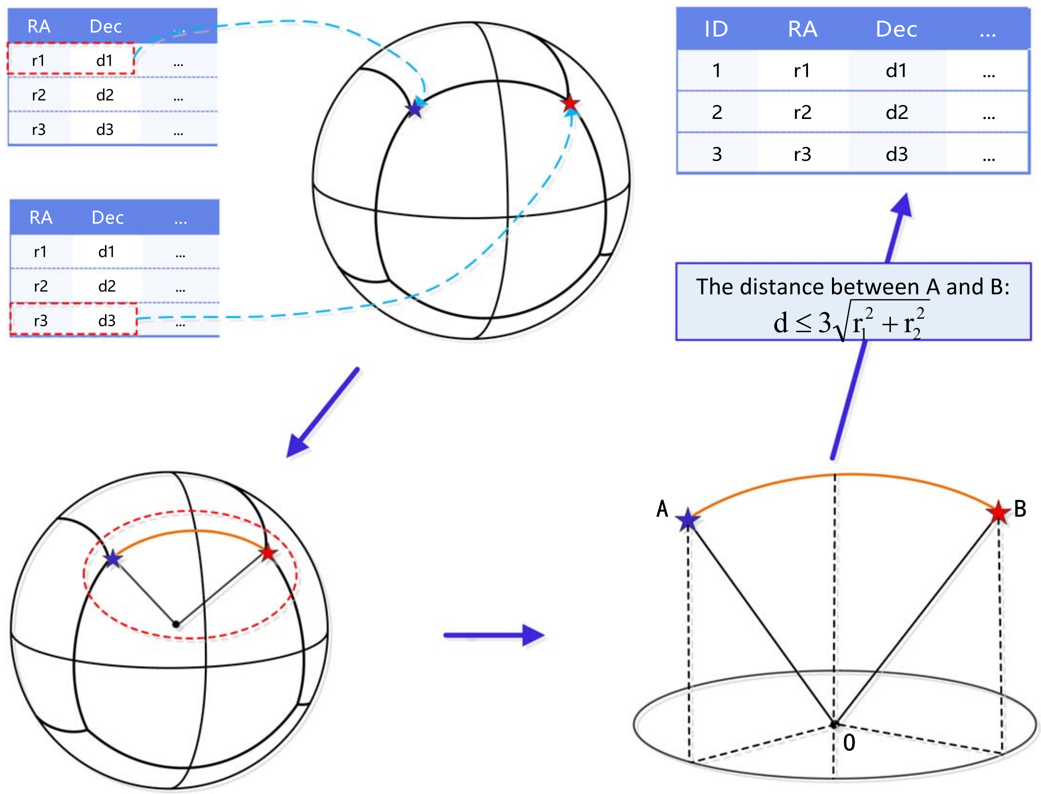


Figure 1. Cross-matching calculation between two astronomical catalogs.

(Demleitner et al. 2014) for the massive astronomical catalogs in XAO-DC. The overall structure of the service is shown in Figure 2. The services were decomposed into (from top to bottom) data layer, calculation layer, and output layer.

(i) *The data layer*. Astronomers upload astronomical catalogs that need to be cross-matching in two ways, via remote URL or local upload as VOtable files. We provide Web, VO tools and Python scripts in three ways to obtain the archived astronomical catalogs of XAO-DC. By 2023 April, we have archived 20 astronomical data catalogs, with catalogs of pulsars, molecular spectra, and active Galactic nuclei from NSRT and catalogs of One-Meter Telescope from NOWT. All astronomical catalogs in XAO-DC are backed up at the headquarters of XAO and Nanshan station.

(ii) *The calculation layer*. The layer is the core part of the whole service, which uses parallel computing techniques for cross-matching calculation. We use the celestial coordinates for cross-matching calculation, that is, calculating the angular distance between two astronomical catalogs. Theoretically, when the angular distance $d \leqslant 3\sqrt{r_1^2 + r_2^2}$, where r_1 and r_2 are the error radius of the two catalogs, the matching of astronomical catalogs are successful. Actually, we calculate d in terms of $d \leqslant \textit{Search radius}$. In order to improve the speed of cross-matching, we use a high performance computing system, which was built in 2016 and named Taurus (Zhang et al. 2018).

(iii) *The output layer*. The layer provides a variety of output formats, such as CSV, HTML, FITS, JSON, etc. Astronomers output and download results of cross-matching according to actual scientific needs. Through the Simple Application Messaging Protocol (SAMP), the results obtained by cross-matching are sent to the standard virtual observatory tool to integrate data visualization and other related tools, supporting astronomers to customize processing of cross-matching calculation and complete the whole process of scientific research and analysis online.

3.2. Indexing Strategy for Astronomical Catalogs

We use Q3C index technology (Koposov & Bartunov 2006) to improve the retrieval efficiency, which is designed for PostgreSQL open source database. There are several reasons

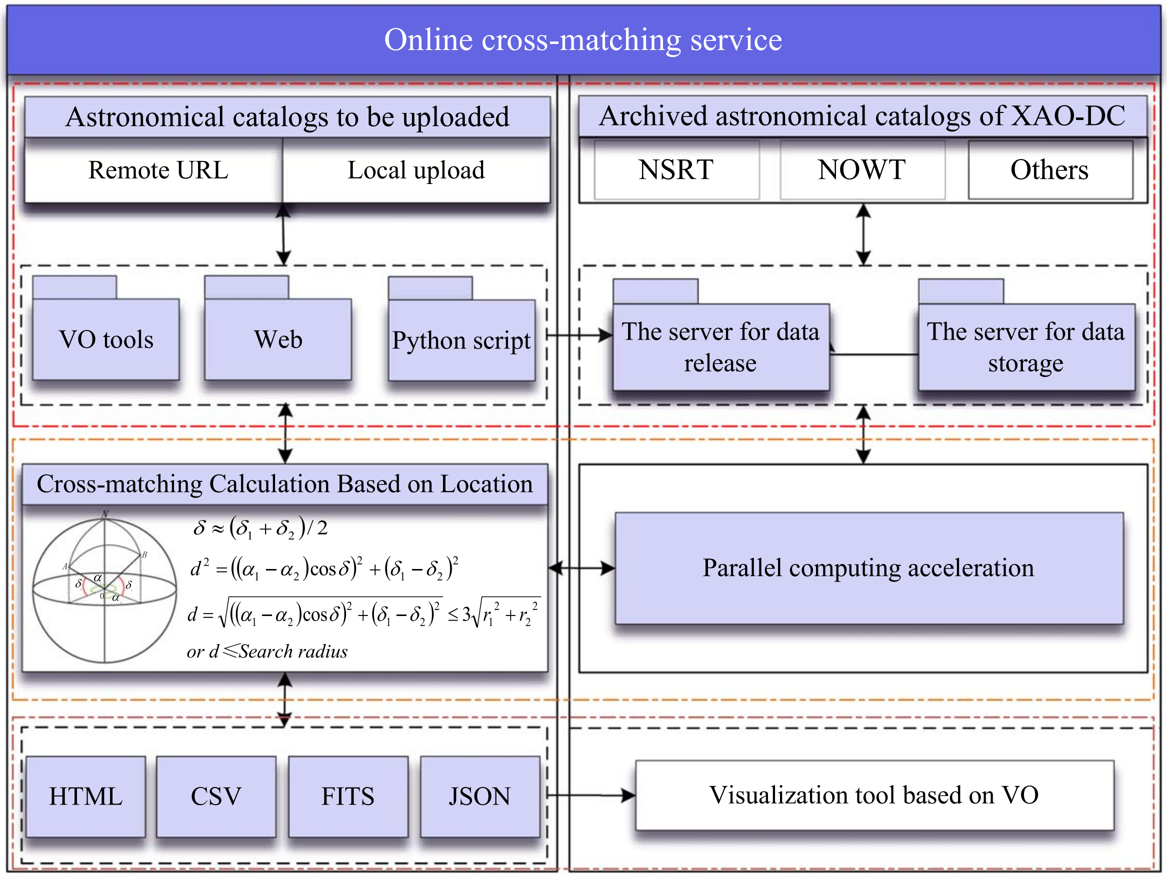


Figure 2. Overview of online cross-matching service.

Table 1
Astronomical Catalogs in XAO-DC (The statistics are available through 2023 April 30)

Catalogs	Wave band	Count	URL
ppmxl.main	Optics	910468688	http://data.xao.ac.cn/ppmxl/q/cone/form
gaia.dr3lite	Optics	1811709771	http://data.xao.ac.cn/gaia/q3/cone/form

for using Q3C: (i) it is optimized for cone search, cross-matching and other technologies, because it uses central projection to reduce a lot of trigonometric function calculation, thus reducing the search time; (ii) it is an open source solution and can be downloaded from http://sourceforge.net/projects/q3c; (iii) it guarantees the best I/O performance for retrieving data from the database. As shown in Figure 3, we assume the celestial sphere is a cube, construct a quadtree on each face of the cube, and use the quadtree structure to generate two-dimensional coordinate codes (or positive integer codes). Since the initial cube has six faces, the mapping to faces can be encoded using a 3-bit binary number. This partition is easily implemented by projecting the surface center of the cube onto the sphere, and the quadtree structure can be automatically inherited by the sphere. Ultimately, the sphere is divided into several quadrilaterals by different levels of partition.

4. Performance of the Cross-matching Service

4.1. Archived Astronomical Catalogs for Cross-matching Service in XAO-DC

We have completed the archiving of observation data of the NSRT and the NOWT, including four data sets, namely pulsar data set, molecular spectral line data set, active galactic nuclei data set and NOWT data set (See Table 1 for the details of each data set). Larger catalogs that can be matched against include

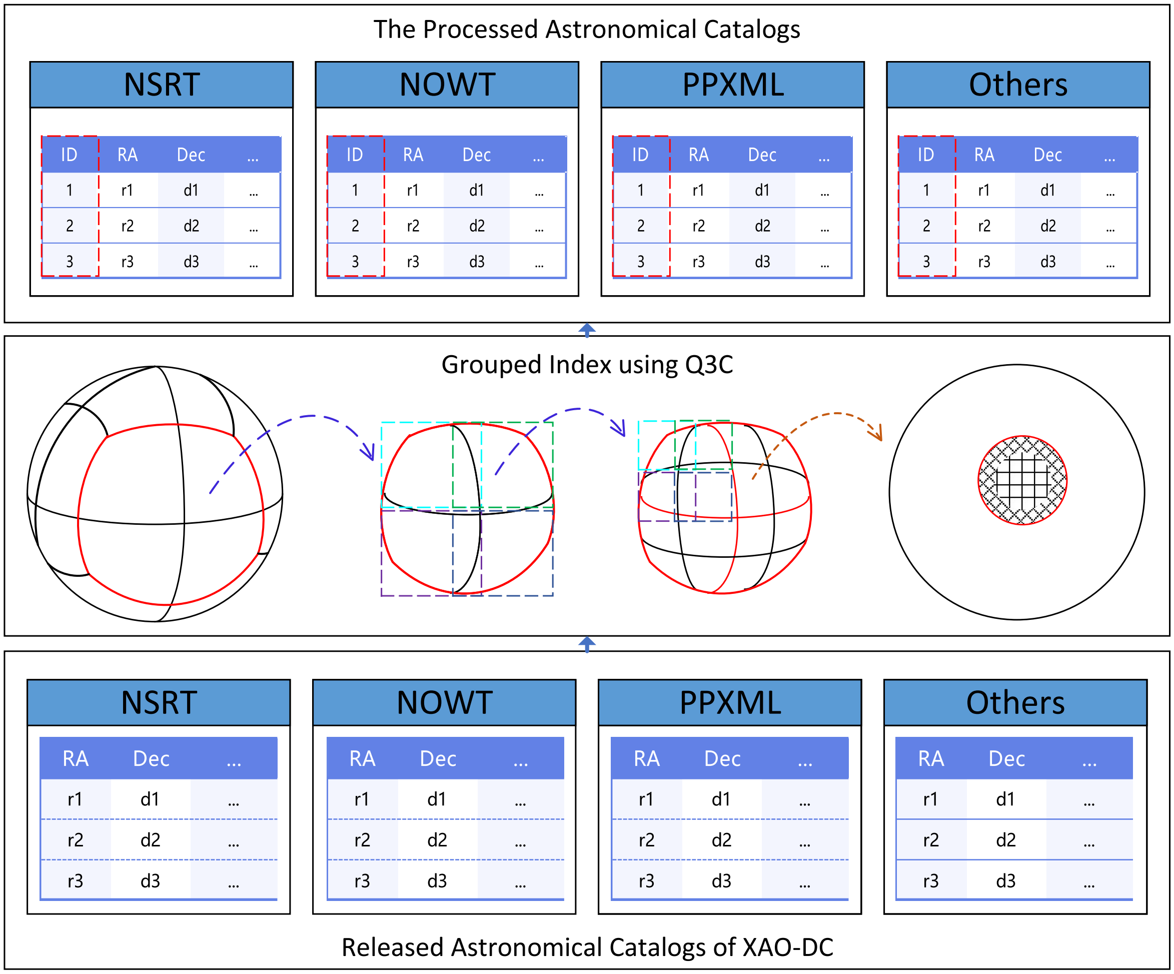


Figure 3. Indexing strategy using Q3C.

Table 2
Input Fields

Name	Table Head	Description
fileSrc	Local file	A local file to upload (overrides remote table if given).
SR	Search radius	Search radius in cross-matching.
tableName	Target Table	Name of the table to match against.
urlSrc	Remote URL	A URL for a table to cross-matching.

Table 3
Experimental Use Case

Parameter	Value	Parameter	Value
Target Table	ppmxl.main	Limit to	10,000
Search radius	0°001	Output format	HTML
Remote URL	http://210.73.36.111/static/cross_match_4000		

Gaia, 2MASS, USNO-B, PPMXL, and more. We use a server with Intel(R) Xeon(R) Silver 4210R CPU @ 2.40 GHz *2, 256 GB memory, 4 TB *2 SSD and 16 TB*60 SATA for online cross-matching experiments.

4.2. Use Case for Cross-matching Service

4.2.1. Input Fields

As shown in Table 2, the fields are available to provide input to the service. The uploaded VOTables must have exactly one pair of columns with UCDs of either pos.eq.[ra|dec]; meta.main or POS_EQ_[RA|DEC]_MAIN. The results of VO cone searches work well. If users have tables of their own, they will first have to bring them to the VOTable format. We currently do not support the transformation of their coordinates, so users have to make sure that the input coordinates match the system used in the table (for basically all of our tables, this means ICRS or FK5 J2000 to an accuracy sufficient for matching). We provide an experimental use case, shown in Table 3, that tests through url: http://data.xao.ac.cn/cross/q/match/form.

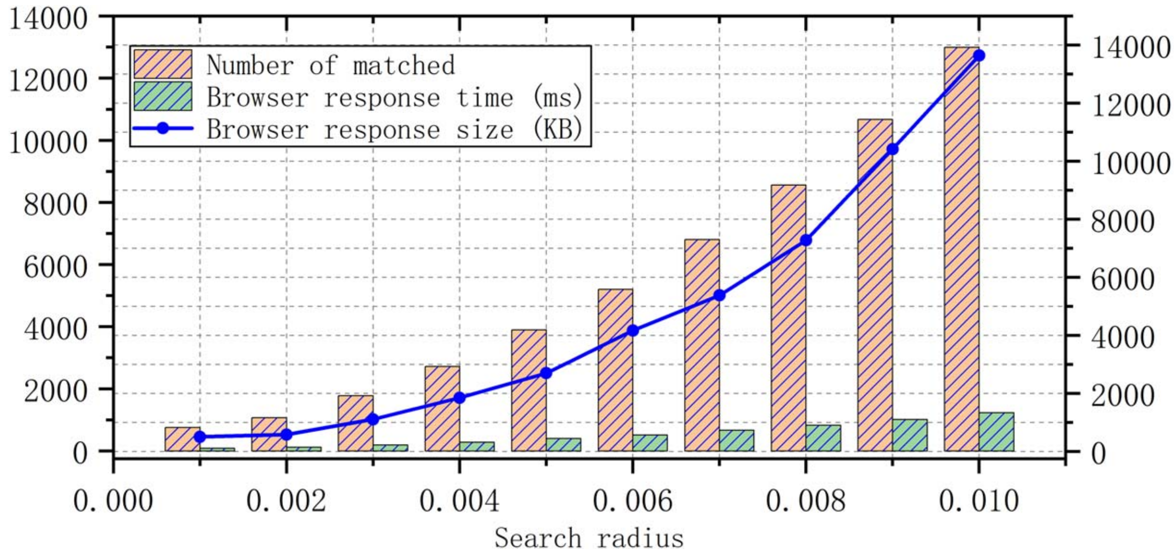


Figure 4. The influence of search radius on experimental results.

Table 4
Cross-matching Results

ID	R.A. (deg)	Decl. (deg)	E_raepra (deg)	E_deepde (deg)	Others	Decl.
1270486784963202545	335.159448	−28.396266	3.69000009e-05	3.69000009e-05	⋯	−28.3958107
1271723434119163981	336.874314	−28.562427	4.52999993e-05	4.52999993e-05	⋯	−28.563134
1272238947138844943	338.898195	−27.889961	4.52999993e-05	4.52999993e-05	⋯	−27.8893547
1272238947067022759	338.898547	−27.889473	3.69000009e-05	3.69000009e-05	⋯	−27.8893547
1273186315633093107	335.85566	−25.841385	4.52999993e-05	4.52999993e-05	⋯	−25.8415443
1273186498931695147	335.856555	−25.841449	3.69000009e-05	3.69000009e-05	⋯	−25.8415443
1276884716561952497	340.584908	−27.463612	4.52999993e-05	4.52999993e-05	⋯	−27.4637784
1279886786271825914	348.146	−35.049952	4.52999993e-05	4.52999993e-05	⋯	−35.0499171
1289552211362865684	352.075615	−31.208315	4.52999993e-05	4.52999993e-05	⋯	−31.2081914
1289552211671667337	352.075928	−31.207844	4.52999993e-05	4.52999993e-05	⋯	−31.2081914
1289979501643796662	350.594732	−29.149134	2.42000006e-05	2.42000006e-05	⋯	−29.14918
1293170549451374502	353.934296	−30.428043	2.47000007e-05	2.47000007e-05	⋯	−30.4280689
1293170549479084174	353.933957	−30.427821	4.52999993e-05	4.52999993e-05	⋯	−30.4280689
1295566798075471614	354.101817	−27.034899	4.52999993e-05	4.52999993e-05	⋯	−27.0341224
1295566799485120388	354.102276	−27.034219	4.52999993e-05	4.52999993e-05	⋯	−27.0341224
1296263507508196424	359.165515	−29.293381	3.69000009e-05	3.69000009e-05	⋯	−29.2931233
1296263507525977872	359.165854	−29.293347	3.69000009e-05	3.69000009e-05	⋯	−29.2931233
1299058494154989044	317.99219	−18.645028	3.69000009e-05	3.69000009e-05	⋯	−18.6451978
1299163679116059348	317.990165	−18.347378	4.52999993e-05	4.52999993e-05	⋯	−18.3476311
1299163679032991356	317.990235	−18.347413	3.18999992e-05	3.18999992e-05	⋯	−18.3476311
1300053359303298668	315.403934	−15.115888	2.08000001e-05	2.08000001e-05	⋯	−15.1159916
1300236670317797321	316.783602	−16.254174	2.75000002e-05	2.75000002e-05	⋯	−16.2542654
…	…	…	…	…	⋯	…
2130664077477512878	33.374175	13.021185	3.69000009e-05	3.69000009e-05	⋯	13.0209357
2132243439030599117	36.323942	12.778484	4.52999993e-05	4.52999993e-05	⋯	12.7788668

4.2.2. Output Result

We obtain the following matched data and corresponding parameter information, including R.A. [deg], decl. [deg], E_raepra [deg], etc, as shown in Table 4 for details of the cross-matching results. At the same time, the result of cross-matching between ppmxl.main (∼1 billion targets) and test catalog (4000 targets) takes less than one second. That

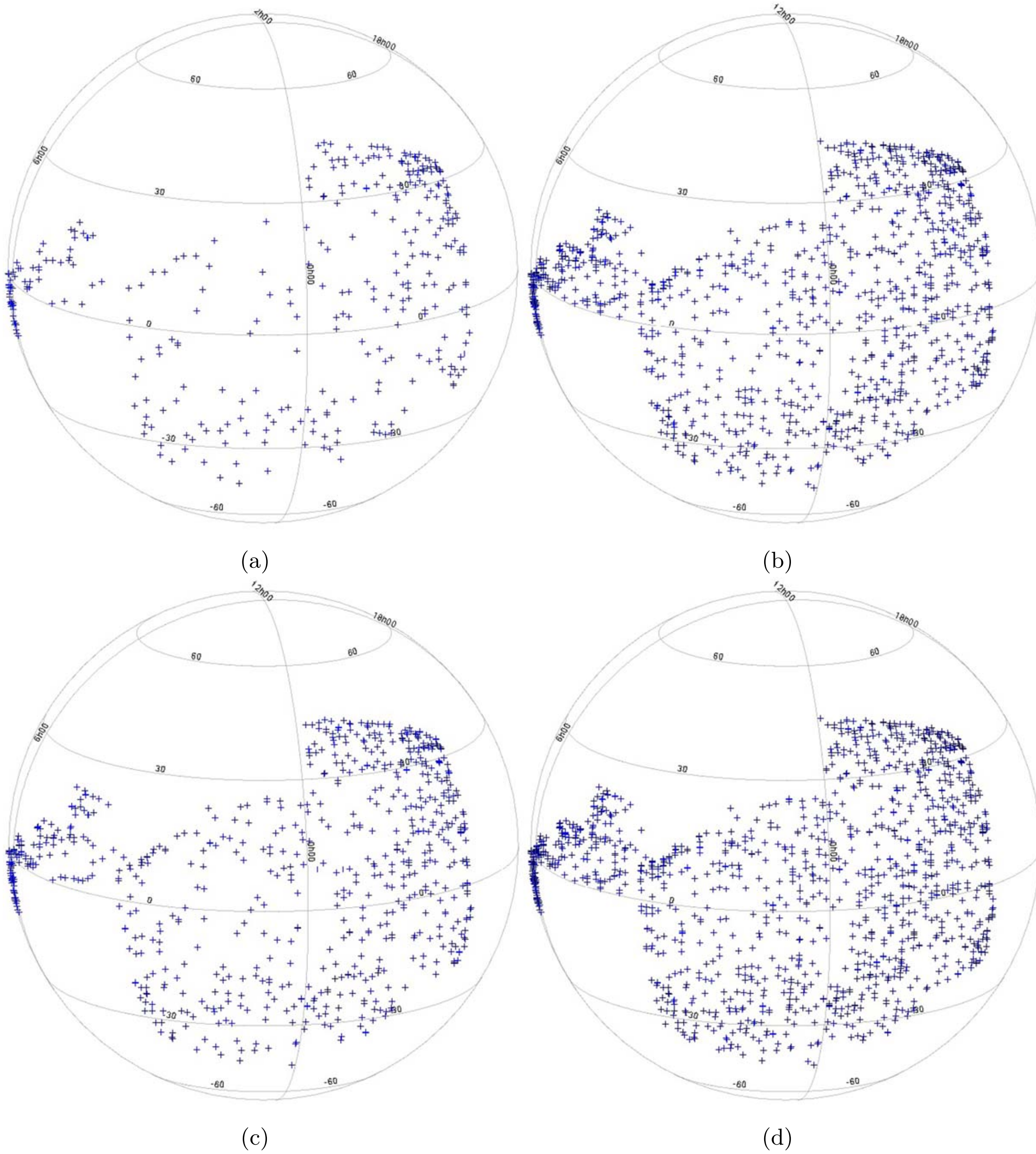
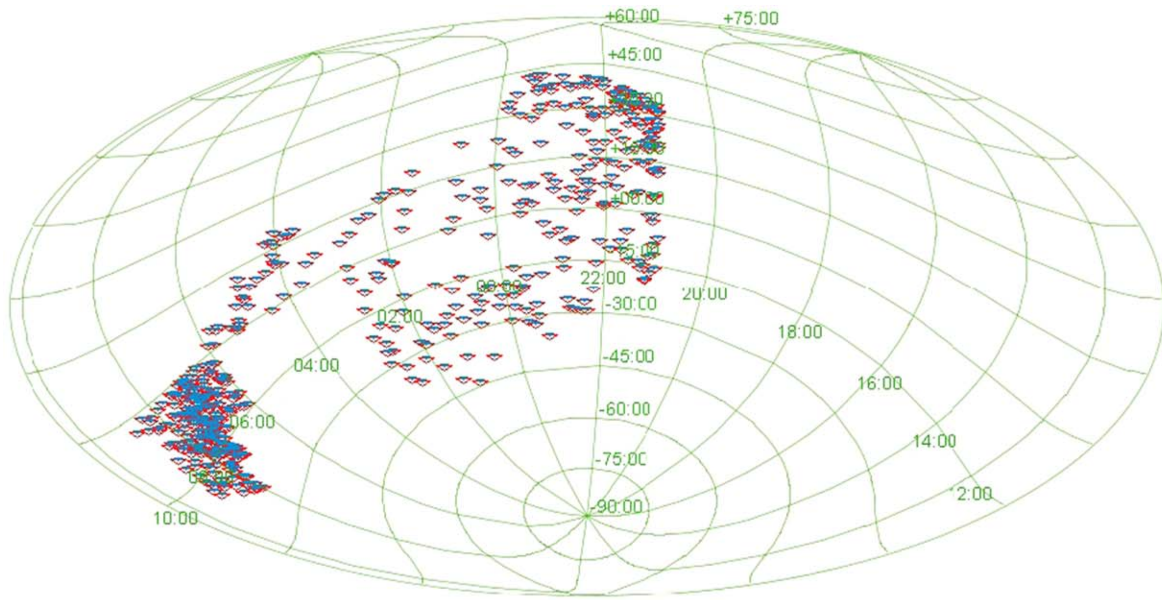


Figure 5. Cross-matching results were obtained by combining TOPCAT, where (a) search radius = $0\overset{\circ}{.}001$; (b) search radius = $0\overset{\circ}{.}004$; (c) search radius = $0\overset{\circ}{.}007$; (d) search radius = $0\overset{\circ}{.}010$. The *x*-coordinate is R.A. [deg] and the *y*-coordinate is decl. [deg]. The rest of the visual results can be accessed from our cross-matching service (URL: http://data.xao.ac.cn/cross/q/match/form), please click "Send via SAMP" after obtaining the matched result.

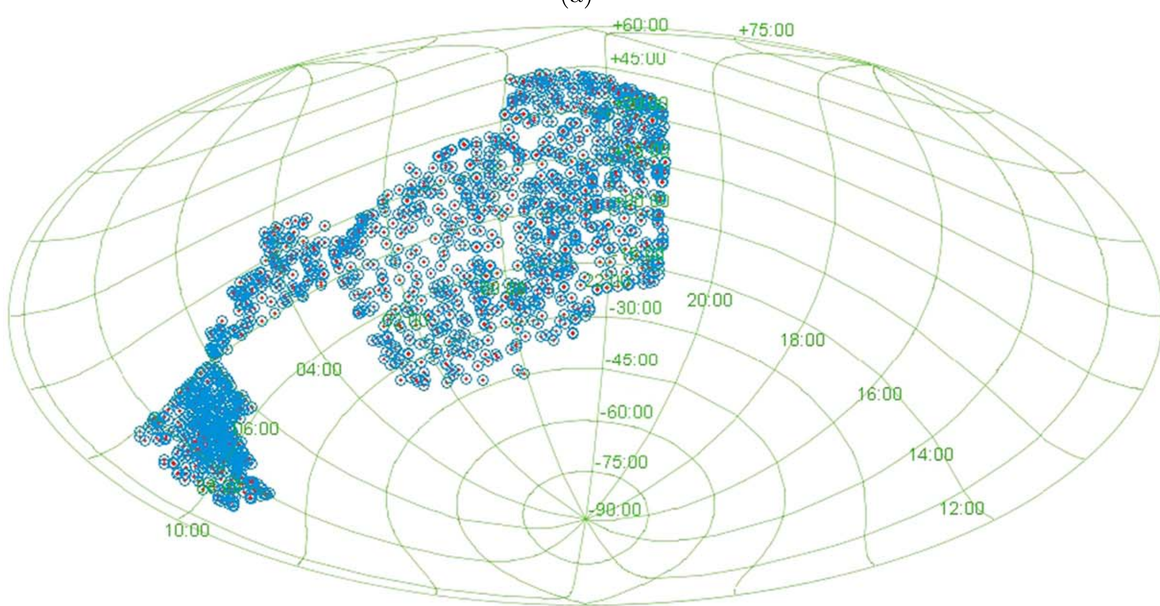
means, our online cross-matching service achieves 4 trillion cross-matching computation results in less than one second. As far as we know, Gao et al. (2008) took 407 minutes (811117 × 470992970); Zhao et al. (2009) took 32 minutes (470992970 × 100106811); Pei et al. (2011) took 10 minutes (470992970 × 100106811); Du et al. (2014) took 7 minutes (946464 × 470992970). Because there is no online platform for testing the methods implemented in the above works, it is impossible to achieve the same scale of cross-matching as in this paper.

4.2.3. The Influence of Search Radius

As shown in Figure 4, We exhibit the corresponding relationship among Number of matched, Browser response time and Browser response size. As the search radius



(a)



(b)

Figure 6. Cross-matching results were obtained by combining TOPCAT, where (a) search radius = $0\overset{\circ}{.}001$; (b) search radius = $0\overset{\circ}{.}010$. The *x*-coordinate is R.A. [deg] and the *y*-coordinate is decl. [deg]. The rest of the visual results can be accessed from our cross-matching service (URL: http://data.xao.ac.cn/cross/q/match/form), please click "Send via SAMP" after obtaining the matched result. Because of the limited space, we present only two results; the rest results can be verified in our cross-matching service.

diminishes (from $0\overset{\circ}{.}010$ to $0\overset{\circ}{.}001$), the Number of matched (from 12,997 to 757), Browser response time (from 13,640 to 503 ms), and Browser response size (from 1228.8 to 89.5 KB) decreased accordingly. This shows that the smaller the search radius, the more accurate the cross-matching results.

4.3. Use Case for Cross-matching Joint Virtual Observatory Tools

In practice, do not use a web browser for cross matching. Instead, obtain a TAP client (e.g., TOPCAT or pyVO), load the table to be matched into the client and then run a query like

(Dowler & Demleitner 2019). Since the backend is the same, the performance characteristics are as for the browser service discussed above.

4.3.1. TOPCAT

TOPCAT[5] is a browser and editor that can interactively graph tables of astronomical data in major formats such as FITS and VOTable. In order to facilitate astronomers to analyze data, we can send the cross-matching results to TOPCAT[6] through SAMP protocol, as shown in Figure 5.

4.3.2. Aladin

Aladin[7] is a free, interactive astronomy software that enables astronomers to interactively retrieve digitized astronomical images from the astronomical catalogs of all known celestial objects, such as Simbad and VizieR, and visually compare them with DSS, PanSTARRS and other astronomical catalogs. To facilitate astronomers to analyze data, we can send the cross-matching results to Aladin[8] through SAMP protocol, as shown in Figure 6.

5. Conclusion

In this paper, we proposed an online cross-matching method based on pseudo-spherical indexing techniques and developed a service combining with Taurus for the XAO-DC to improve cross-matching efficiency. This service supports two source table file input modes: local upload and URL; file input supports the standard VOTable format, and realizes the cross-matching calculation between the uploaded astronomical catalogs and the released astronomical catalogs in the XAO-DC. At the same time, it supports HTML, CSV, FITS, JSON and other data output modes, and integrates necessary visualization tools (such as TOPCAT, Aladin, etc.) according to the related protocols of the virtual observatory to support the processing and customization of the data after cross-matching. The service provides astronomers with reliable and convenient technical support, which is intended to help them further their astronomical research.

Acknowledgments

This work is supported by the National Key R&D Program of China (Nos. 2022YFF0711502 and 2021YFC2203502); the National Natural Science Foundation of China (NSFC) (12173077 and 12003062); the Tianshan Innovation Team Plan of Xinjiang Uygur Autonomous Region (2022D14020); the Tianshan Talent Project of Xinjiang Uygur Autonomous Region (2022TSYCCX0095); the Scientific Instrument Developing Project of the Chinese Academy of Sciences (grant No. PTYQ2022YZZD01); China National Astronomical Data Center (NADC); the Operation, Maintenance and Upgrading Fund for Astronomical Telescopes and Facility Instruments, budgeted from the Ministry of Finance of China (MOF) and administrated by the Chinese Academy of Sciences (CAS); Natural Science Foundation of Xinjiang Uygur Autonomous Region (2022D01A360). This work is supported by Astronomical Big Data Joint Research Center, co-founded by National Astronomical Observatories, Chinese Academy of Sciences.

ORCID iDs

Jie Wang https://orcid.org/0000-0003-0380-6395
Xu Du https://orcid.org/0000-0001-6448-0822

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[5] https://www.star.bris.ac.uk/mbt/topcat/
[6] To test this feature, users need to download and install TOPCAT first.
[7] http://aladin.cds.unistra.fr/aladin.gml
[8] To test this feature, users need to download and install Aladin first.