

Development of 2MASS Catalog Server Kit

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ABSTRACT. We develop a software kit called “2MASS Catalog Server Kit” to easily construct a high-performance database server for the 2MASS Point Source Catalog (includes 470,992,970 objects) and several all-sky catalogs. Users can perform fast radial search and rectangular search using provided stored functions in SQL similar to SDSS SkyServer. Our software kit utilizes open-source RDBMS, and therefore any astronomers and developers can install our kit on their personal computers for research, observation, etc. Our kit is tuned for optimal coordinate search performance. We implement an effective radial search using an orthogonal coordinate system, which does not need any techniques that depend on HTM or HEALpix. Applying the *xyz* coordinate system to the database index, we can easily implement a system of fast radial search for relatively small (less than several million rows) catalogs. To enable high-speed search of huge catalogs on RDBMS, we apply three additional techniques: table partitioning, composite expression index, and optimization in stored functions. As a result, we obtain satisfactory performance of radial search for the 2MASS catalog. Our system can also perform fast rectangular search. It is implemented using techniques similar to those applied for radial search. Our way of implementation enables a compact system and will give important hints for a low-cost development of other huge catalog databases.

Online material: color figure

1. INTRODUCTION

Using huge object catalogs is more common in astronomical studies and observations. To support searching such catalogs, a variety of World Wide Web-based database services have been developed. For example, NASA/IPAC Infrared Science Archive (IRSA; Berriman et al. 2000), VizieR (Ochsenbein et al. 2000), and Virtual Observatory (VO; Szalay 2001) portal sites are widely used in astronomical communities. Some project teams distribute software to be installed in personal computers to use such services via a network. Astronomers and developers can use various catalogs with Web browsers and such client-side software.

On the other hand, there is software to search catalogs in offline environments. For example, “scat” in the WCSTools package (Mink 2006) is widely used in astronomical communities. Such software is important for observatories with unstable or narrowband networks or for personal studies that require huge catalog entries. Although SkyServer (Thakar et al. 2004) of Sloan Digital Sky Survey (SDSS; York et al. 2000) shows powerful flexibility of the programming interfaces based on Structured Query Language (SQL) for catalog search, it is not easy for end users to have such a high-performance search server in offline environments.

Therefore, we develop a software kit that enables any users to construct a database system based on a relational database management system (RDBMS) in their personal computers

and to quickly search a huge catalog with functions similar to SDSS SkyServer. The first target of our kit is the Two Micron All Sky Survey (Skrutskie et al. 2006) Point Source Catalog (2MASS PSC), which is huge but frequently used in astronomy. We implement powerful functions into the kit using our various techniques. One of the features of our techniques is applying an *xyz* coordinate system for fast radial search of a huge catalog. This implementation might be rare and interesting for developers, and we mainly report it in this article.

Our software kit is built on publicly available software. In contrast, commercial RDBMS products have been used to develop previous Web-based database services of huge catalogs such as SDSS SkyServer (Thakar et al. 2004), WFCAM Science Archive (Hambly et al. 2007), etc. This article will also demonstrate the true power of an open-source RDBMS.

This article is organized as follows: First, our software kit is introduced in § 2. We show our overview of software design in § 3. In § 4, we explain details of our techniques and reasonable implementation for high-speed radial search of our software kit. We additionally report techniques for rectangular search in § 5. Summary is given in § 6.

Note that primitive data types of RDBMS are displayed in the following way throughout this article: INT2 is a signed two-byte integer, INT4 is a signed four-byte integer, and FLOAT8 is a double-precision floating-point number.

2. 2MASS CATALOG SERVER KIT

The 2MASS Catalog Server Kit¹ (2MASS Kit) is a software package to construct a high-performance search server of 2MASS PSC and several all-sky catalogs on Linux, MacOSX, Solaris, and other UNIX systems. To install this kit, it is enough to prepare a standard personal computer with a hard drive of 600 GB or more.

The kit contains a complete data set of tables for 2MASS PSC, SQL statements and sources of C language with a Makefile. The HTML document (Fig. 1) shows step-by-step instructions for installation, a tutorial for database beginners, reference of stored functions, and several hints for tuning. The instructions include a procedure for setting up RDBMS and configuration of the operating system; therefore, any users can easily construct their own catalog database servers. Users can search catalogs not only with flexible SQL, but also with several useful stored functions prepared by our kit. Using the functions in users' SQL statements, users can perform fast radial and rectangular search with very small SQL statements with coordinate conversions (e.g., J2000 to Galactic). Of course, users do not have to know algorithm and indexing about typical searches. We show an example SQL statement of a radial search of Galactic coordinate (0,0) with 0.2' radius:

```
SELECT fJ2L(o.ra,o.dec) as l,
       fJ2B(o.ra,o.dec) as b,
       o.j_m,o.h_m,o.k_m, n.distance
FROM fTwomassGetNearbyObjEq(
        fG2Ra(0,0),fG2Dec(0,0),0.2) n,
       twomass o
WHERE n.objid = o.objid;
```

where `fJ2L()` and `fJ2B()` convert J2000 to Galactic, `fG2Ra()` and `fG2Dec()` convert Galactic to J2000, and `fTwomassGetNearbyObjEq()` is a stored function that performs fast radial search of 2MASS PSC with an optimized algorithm.

The kit is also characterized by its flexible tuning. Each table and index for 2MASS PSC is registered in one of seven table spaces (each resides in a separate directory), thus allowing only the essential parts to be easily moved onto fast devices. Given the terrific evolution that has taken place with recent solid-state drives (SSDs) in performance, a very cost-effective way of constructing high-performance servers is moving part, or all, of the table indices to a fast SSD.

Before installing the 2MASS Kit, users can confirm the performance of our kit using the SQL Search Tool² of the *AKARI* Catalogue Archive Server (*AKARI*-CAS; Yamauchi et al. 2011). *AKARI*-CAS is developed to search *AKARI* All-Sky Catalogues

¹ Software package and data set are available at <http://www.ir.isas.jaxa.jp/~cyamauch/2masskit/>. We are planning to support USNO-B1.0, PPMXL, GSC-2.3, etc.

² See <http://darts.jaxa.jp/ir/akari/cas/tools/search/sql.html>.

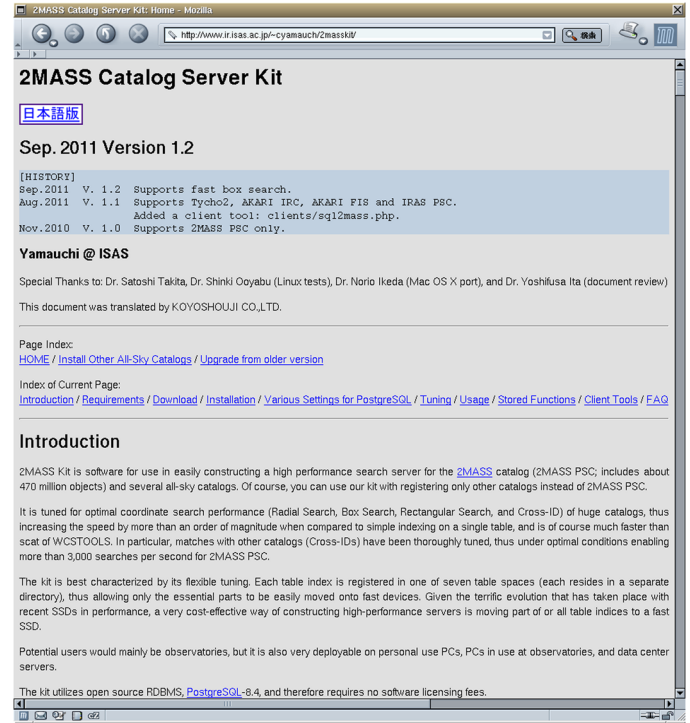


FIG. 1.—Web page of the 2MASS Catalog Server Kit. Users can easily install, use, and tune their own catalog database. This page includes enough contents for RDBMS beginners. See the electronic edition of the *PASP* for a color version of this figure.

based on imaging data obtained by the Far-Infrared Surveyor (FIS; Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007) built on the *AKARI* satellite, and it also supports fast search for 2MASS PSC. To perform this search, *AKARI*-CAS has the source codes of the 2MASS Kit. Of course, our kit utilizes open-source RDBMS, PostgreSQL-8.4, and therefore requires no software licensing fees.

3. OVERVIEW OF SOFTWARE DESIGN

Choosing an appropriate RDBMS product is important for our software design, since functions to support various users' requirements depend on RDBMS products.

Users will search the 2MASS PSC using various criteria. Therefore, the RDBMS product should meet recent SQL standards and must have enough search performance. In addition, some users might not have knowledge about indices of tables. To support such users, the kit has to provide some functions to minimize SQL statements for typical searches in astronomy. Therefore, the RDBMS product should have high coding flexibility of stored functions. We investigated some open-source RDBMS products when developing *AKARI*-CAS. We found that PostgreSQL perfectly satisfies the preceding requirements. See also Yamauchi et al. (2011) for an investigation about RDBMS products.

Fast positional search is indispensable for astronomy, even if the database has huge catalogs. Fortunately, PostgreSQL has some special features to handle huge tables. For example, PostgreSQL supports table inheritance that is useful for table partitioning and has a “constraint-exclusion” feature to allow us a seamless access to the partitioned tables. To obtain the best performance of positional search, i.e., radial search and rectangular search, we apply such features and write our codes in stored functions for more optimization.

We mainly tune the performance of radial search, since it is most important for astronomical catalog databases. Our severe test for it is done by cross-identification as multiple radial searches. It is the main theme of this article.

One of the advantages of PostgreSQL is having many built-in functions usable in SQL statements. Together with them, coordinate conversions shown in § 2 such as J2000-to-Galactic conversion are supported by newly created stored functions that contain some codes of *wcstools*-3.8.³ Our kit provides further functions that are also available in *AKARI*-CAS. See Yamauchi et al. (2011) for general technical know-how for creating stored functions in PostgreSQL.

4. TECHNICAL DESIGN OF RADIAL SEARCH

4.1. Basic Algorithm

The radial search is the most typical query in the catalog database services. However, this search using RDBMS cannot be optimized in a straightforward way, because an index of RDBMS is useful for the case:

$$S_{\min} \leq f(c_{A_n}, c_{B_n}, \dots, c_{X_n}) \leq S_{\max}, \quad (1)$$

where S_{\min} and S_{\max} are the search criteria, and c_{A_n}, c_{B_n}, \dots are data of columns A, B , etc.; however, an index cannot be created for following case:

$$S_{\min} \leq f(c_{A_n}, c_{B_n}, S_1, S_2) \leq S_{\max}, \quad (2)$$

where S_1 and S_2 are also the search criteria. The radial search corresponds to the case (eq. [2]), i.e., $f()$ is a function that takes a pair of positions and returns an angular distance, and S_{\max} is the search radius.

To enable fast radial search applying the database index, some special methods based on spatial splitting have been devised, such as Hierarchical Triangular Mesh⁴ (HTM; Kunszt et al. 2000) or HEALPix⁵ (Górski et al. 2005). Their methods divide the sky into many areas, assign each area the unique identification, and give each object a corresponding identification from which the one-dimensional index is created.

We do not use such techniques, but use the more simple and cost-effective way. Figure 2 shows the concept of our radial search. The most important point of this concept is the use of the xyz coordinate for the database index.

In our databases, the object tables have columns of unit vectors (cx, cy, cz) presenting J2000 source positions. We create a composite index on (cx, cy, cz) and write stored functions to execute the following procedure:

1. Catch objects within a cube of the size $2r \times 2r \times 2r$ using index scan on (cx, cy, cz).
2. Select objects within the strict search circle on the celestial sphere from the result of step 1.

The feature of our algorithm is that it requires almost no calculation before executing the index scan, and the efficiency is quite high for a small search radius. In addition, we do not have to implement special processing for polar singularity. Tanaka (1993) pointed out the advantage of applying orthogonal coordinate system to avoid polar singularity.

4.2. Implementation for Small Catalogs

In this section, we present our implementation and test results of radial search of the *AKARI*/IRC Point Source Catalogue (*AKARI*/IRC PSC; Ishihara et al. 2010), including 870,973 objects. It is relatively small compared with the SDSS or 2MASS catalog; therefore, we implement the system only with the basic method described in § 4.1.

To enable fast radial search, we construct our table and index with the following procedure:

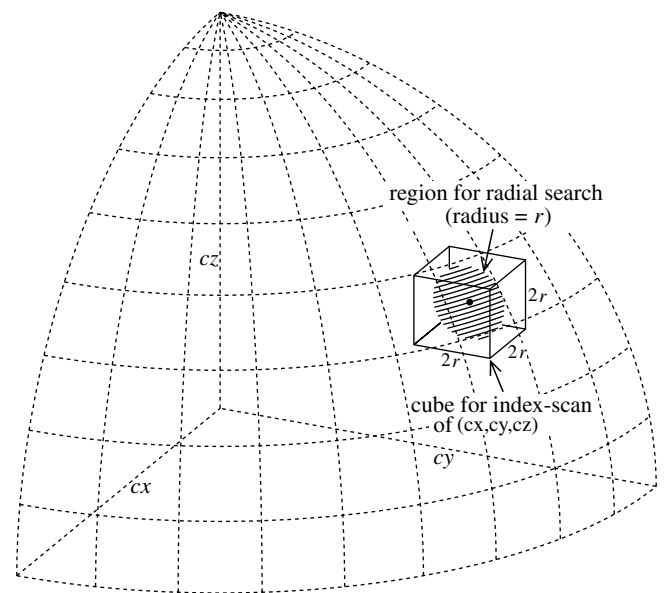


FIG. 2.—Concept of our radial search with search radius = r . Catch objects within a cube $2r$ each side using index scan on (cx, cy, cz), then select objects within the strict search area (striped pattern) from them.

³ See <http://tdc-www.harvard.edu/wcstools/>.

⁴ See <http://skyserver.org/HTM/>.

⁵ See <http://healpix.jpl.nasa.gov/>.

1. Register all rows of all columns of *AKARI/IRC* PSC into a table *AkariIrc*. The table includes a primary key *objID* of INT4 type, J2000 source position (*ra*, *dec*) of FLOAT8 type, and unit vector (*cx*, *cy*, *cz*) of FLOAT8 type converted from (*ra*, *dec*).

2. Create a composite index on (*cx*, *cy*, *cz*) by the following SQL statement:⁶

```
CREATE INDEX akariirc_xyz
ON AkariIrc(cx,cy,cz);
```

To perform a radial search, we create SQL stored functions. For example, the source code of a stored function to obtain an *objID* of the object whose distance from search position is the smallest in the search region is given next:⁷

```
CREATE FUNCTION
    fAkariIrcGetNearestObjIDEq(FLOAT8,
                                FLOAT8,FLOAT8)

RETURNS INT4 AS
'SELECT o.objid
FROM (
    SELECT objid,
           fDistanceArcMinXYZ(fEq2X($1,$2),
                               fEq2Y($1,$2),fEq2Z($1,$2),
                               cx,cy,cz) as distance
FROM AkariIrc
WHERE
    (cx BETWEEN fEq2X($1,$2) - fArcMin2Rad($3)
     AND fEq2X($1,$2) + fArcMin2Rad($3))
AND
    (cy BETWEEN fEq2Y($1,$2) - fArcMin2Rad($3)
     AND fEq2Y($1,$2) + fArcMin2Rad($3))
AND
    (cz BETWEEN fEq2Z($1,$2) - fArcMin2Rad($3)
     AND fEq2Z($1,$2) + fArcMin2Rad($3))
) o
WHERE o.distance <= $3
ORDER BY o.distance
LIMIT 1'
IMMUTABLE LANGUAGE 'sql';
```

where \$1, \$2, and \$3 are the arguments of this stored function; (\$1, \$2) is the center position in J2000 of the search region; and \$3 is the search radius.

If we cut out from `SELECT o.objID` to `WHERE o.distance <= $3` in the preceding source and execute it by giving actual values for \$1, \$2, and \$3, it performs a radial search.

To evaluate the performance of our radial search, we try a cross-identification as multiple radial searches using

TABLE 1

RESULTS OF MATCH-UP OF *AKARI/FIS* BSC WITH *AKARI/IRC* PSC

Condition	Elapsed time
Just after OS rebooting	42.0 s
Second trial	19.8 s

NOTE.—The hardware is a Core2Quad Q9650 (3.0 GHz) CPU on GIGABYTE GA-EX38-DS4 with 8 Gbyte DDR2-800 memory and an Adaptec RAID 2405 with 1 Tbyte SATA2 HDD × 2 (RAID1).

`fAkariIrcGetNearestObjIDEq()`. We show our test results of matching up all objects of *AKARI/FIS* Bright Source Catalogue⁸ (*AKARI/FIS* BSC; including 427,071 objects; Yamamura et al. 2010) with all *AKARI/IRC* PSC objects within 0.25' radius in Table 1. Here is the SQL statement for this test:

```
SELECT count(
    fAkariIrcGetNearestObjIDEq(ra,dec,0.25))
FROM AkariFis;
```

This returns 19,267 matches.

AKARI catalogs are small enough compared with memory capacities of present computers. Therefore, users generally have to wait only 30 s or so, even for cross-identification. We can implement radial search of the catalogs including less than several million objects with our simple method by applying the *xyz* coordinate. See also Yamauchi et al. (2011) for more applications for *AKARI* catalogs using our techniques.

4.3. Implementation for 2MASS PSC

4.3.1. Data Size Limit of Simple Radial Search Implementation

In § 4.2, we store all the contents of a catalog into a table, create a composite index on (*cx*, *cy*, *cz*), and write a simple SQL stored function to perform a radial search. However, there is a limit of row numbers for this simple implementation described in § 4.2. This limit is caused by two factors: (1) enlargement of processing and (2) the bottleneck of disk I/O access. First, we show the behavior of factor 1 here.

We test the performance of cross-identification as multiple radial searches. We use a subset of *AKARI/IRC* PSC and a subset of 2MASS PSC for the cross-identification. The table of the subset of 2MASS PSC includes all columns and additional primary key *objid* of INT4 and unit vector (*cx*, *cy*, *cz*) of FLOAT8 calculated at the data registration, and a composite index on the unit vector is created. To examine the performance

⁶In the case of PostgreSQL, we have to do `VACUUM ANALYZE`; after creating indices.

⁷See Appendix A for each stored function written in this definition.

⁸*AKARI/FIS* All-Sky Survey Bright Source Catalogue Version 1.0 Release Note (Yamamura et al. 2010), http://www.ir.isas.jaxa.jp/AKARI/Observation/PSC/Public/RN/AKARI-FIS_BSC_V1_RN.pdf.

dependency on the number of data entries, we prepare five cases; 5,099,652, 10,226,706, 20,294,711, 40,688,903, and 82,092,729, selected by declination range from the south pole. Then we test the performance of cross-identification for each case. The following SQL statement is an example of the test:

```
SELECT count(
  fTwomassGetNearestObjIDEq(o.ra,o.dec,0.25))
FROM (SELECT * FROM AkariIrc
      WHERE dec < -74.600006) o;
```

A criterion of $\text{dec} < -74.600006$ is to choose *AKARI/IRC* objects within the region corresponding to the 2MASS PSC subset.

Figure 3 shows the result of our tests. In the case of the smallest data size of about 5.1 million objects, searches of more than 3000 counts s^{-1} are performed. However, processing speed is rapidly dropped with increasing number of rows. Each measurement in Figure 3 was obtained from the median of the last three successive runs; i.e., all measurements were taken under the condition of enough cached data in the main memory. Therefore, this result means that it is impossible to obtain acceptable performance for severe search requirements with huge catalogs using this simple implementation, even if there is no bottleneck of disk I/O access.

4.3.2. Strategy to Break the Data Size Limit

As shown in § 4.3.1, we cannot achieve sufficient performance under severe search requirements of huge catalogs using simple implementation. Moreover, we can easily expect that the bottleneck of disk I/O becomes a serious problem for actual use. To break such limits, we consider to optimize the design of table relations, indices, and stored functions. Our strategy for implementation of huge catalogs is as follows:

1. Reduce the height of the nonunique index.
2. Reduce the file size of the data set for performing a radial search.
3. Note that unique indices (e.g., primary key) give enough performance for a huge table.
4. Minimize CPU time for additional processing.
5. Carry out experimental tuning.

4.3.3. Design of Table Relation

Considering the strategy in § 4.3.2, we determine the design of table relation as follows:

1. We apply the table partitioning technique.
2. We prepare a special table set consisting of only necessary columns for each search purpose.
3. We store the object positions into integer (INT4) columns in this special table set. These integer values are converted and scaled from the original floating-point values of right ascension and declination.

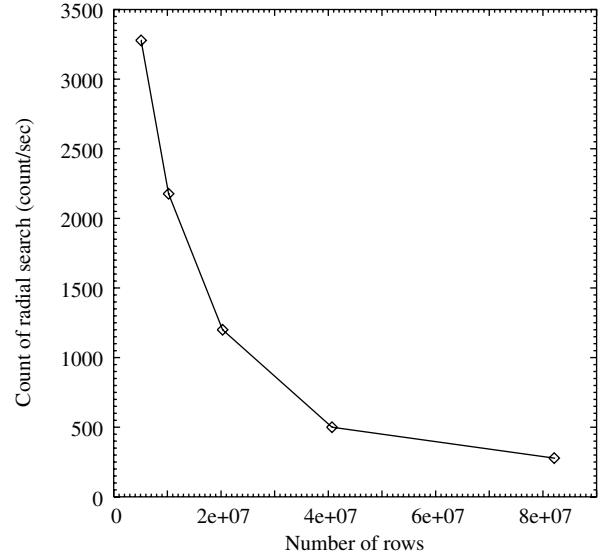


FIG. 3.—Performance test of simple radial search implementation applied for a huge catalog. We test cross-identification between a subset of *AKARI/IRC* PSC and subset of 2MASS PSC for different row sizes of the 2MASS PSC table; count of radial search per second is plotted against the number of rows in the 2MASS PSC table. Hardware is a 2× Opteron2384 CPU on a Supermicro dual-processor board with 32 Gbyte memory.

Figure 4 shows our design of table relation. The main table “twomass” has 470,992,970 entries (without partitioning⁹) and is basically supposed to be searched with the primary key. On the other hand, table partitioning is applied to the table sets “twomass_xyzi” and “twomass_j2000i” to reduce the height of the nonunique index in each table. These two table sets are optimized for radial search and rectangular search (see § 5), respectively.

Table partitioning is supported via table inheritance in PostgreSQL. A parent table has column definition and empty rows, and child tables have the same columns as those of the parent and a number of rows. We determine the contents of child tables with the range partitioning using values of declination. This partitioning is implemented so that child tables have almost the same number of rows. The optimal number of partitions is discussed in § 4.3.6.

The values of (c_{xi} , c_{yi} , c_{zi}) are converted from the original right ascension and declination and scaled between -2×10^9 and 2×10^9 (integer) so that the spatial resolution is fine enough for astronomical object catalogs. When performing a radial search, this integer version of the unit vector is restored into floating-point values to calculate angular distance.

The data size of the table set is about 20 Gbyte, which reduces disk read traffic and disk seek time.

⁹ In our tests, partitioning of main table decreases the performance of join on the primary key.

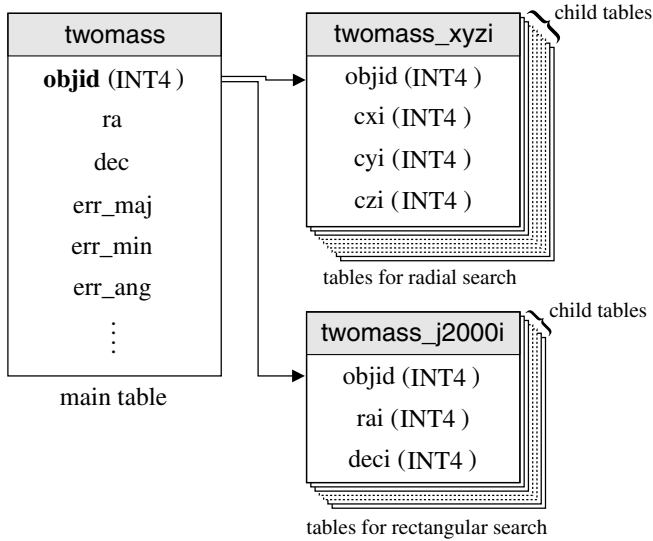


FIG. 4.—Design of table relation to enable fast positional search of 2MASS. Columns (cxi, cyi, czi) and (rai, deci) are the unit vectors, right ascension, and declination, respectively. Their integer values are converted and scaled from floating-point values in columns (ra, dec) in the twomass table.

4.3.4. Index

We can notice that spatial resolution of the composite index on (cxi, cyi, czi) does not have to be that of INT4, since the index is only used to preselect objects within a cube. Therefore, we can reduce the size of the index on (cxi, cyi, czi) using the composite expression index so that the index is created in INT2 type.

We show an actual SQL statement to create one of the indices:

```
CREATE INDEX twomass_xyzi_aaa0_i16xyz
ON twomass_xyzi_aaa0
(fGetI16UVecI4(cxi,32400),
 fGetI16UVecI4(cyi,32400),
 fGetI16UVecI4(czi,32400));
```

where twomass_xyzi_aaa0 is the name of a child table and fGetI16UVecI4(arg, 32400) scales and rounds the unit vector of INT4 into that of INT2 having a range from $-32,400$ to $32,400$. This gives about $9''$ of spatial resolution in the worst case; however, it does not cause any problems for typical searches.

The data size of all indices on table sets twomass_xyzi is about 10 Gbyte, which is small enough to be stored in a RAM disk and enables faster file access.

4.3.5. Stored Function

PostgreSQL has a constraint-exclusion (CE) feature to allow us a seamless access to the partitioned tables. If CHECK constraints are included in the definitions of child tables, the server

parses an SQL statement referring a parent and accesses only necessary child table(s). We find that CE can improve the performance of a general one-time search.¹⁰ However, it is still not enough for repeating a radial search many times within a small period of time. It is desired that cross-identification can be also performed only with an SQL statement that runs multiple radial searches.

To improve the performance further, we create a stored function to access necessary child tables and perform a radial search. Although it is best to write the code in C from a performance point of view, an SQL execution in a C stored function is not supported in PostgreSQL. Alternatively, PostgreSQL offers dynamic SQL execution in PL/pgSQL¹¹; therefore, we create stored functions in both PL/pgSQL and C. We show a code to create a PL/pgSQL function that obtains an objID of the object nearest to the given position within the search region (this function is used for cross-identification):

```
CREATE FUNCTION fTwomassGetNearestObjIDEq(
    arg1 FLOAT8, arg2 FLOAT8, arg3 FLOAT8)
RETURNS INT4
AS $$
DECLARE
    rt INT4;
BEGIN
    EXECUTE _fTwomassGetSqlForRadialSearch(
        arg1, arg2, arg3, 32400, TRUE
    ) INTO rt;
    RETURN rt;
END
$$ IMMUTABLE LANGUAGE 'plpgsql';
```

where _fTwomassGetSqlForRadialSearch() is a stored function written in C that returns an SQL statement for radial search or cross-identification (i.e., multiple radial searches), and arg1, arg2, and arg3 are right ascension, declination, and search radius, respectively. The fourth and fifth arguments of _fTwomassGetSqlForRadialSearch() are the scaling parameter of a composite expression index on (cxi, cyi, czi) and a switch to select either radial search (FALSE) or cross-identification (TRUE), respectively.

The function _fTwomassGetSqlForRadialSearch() knows range information of declination for each child table of twomass_xyzi and generates an appropriate SQL statement with the UNION ALL¹² keyword (if required) to access necessary child table(s). We show an example SQL statement generated by the function that searches the nearest object from (0,0) in J2000 coordinates within a $10'$ radius:

¹⁰ We apply CE for rectangular search. See § 5.

¹¹ PL/pgSQL is a procedural language for the PostgreSQL database system.

¹² UNION ALL is used to merge two results of SELECT phrases.

```

SELECT o.objid
FROM
  (SELECT objid,
    fDistanceArcMinXYZI4(
      cxi,cyi,czi,1,0,0) AS distance
  FROM twomass_xyzi_ace7
  WHERE (fGetI16UVecI4(cxi,32400)
    BETWEEN 32305 AND 32400) AND
    (fGetI16UVecI4(cyi,32400)
    BETWEEN -95 AND 95) AND
    (fGetI16UVecI4(czi,32400)
    BETWEEN -95 AND 95)
  UNION ALL
  SELECT objid,
    fDistanceArcMinXYZI4(
      cxi,cyi,czi,1,0,0) AS distance
  FROM twomass_xyzi_baa0
  WHERE (fGetI16UVecI4(cxi,32400)
    BETWEEN 32305 AND 32400) AND
    (fGetI16UVecI4(cyi,32400)
    BETWEEN -95 AND 95) AND
    (fGetI16UVecI4(czi,32400)
    BETWEEN -95 AND 95)
  ) o
WHERE o.distance <= 10
ORDER BY o.distance
LIMIT 1

```

Here, `fDistanceArcMinXYZI4()` is a stored function written in C to obtain angular distance in arcminutes between two positions.

General radial search is performed by using the `fTwomassGetNearbyObjEq()` function. The source code of it is almost the same as that of `fTwomassGetNearestObjIDEq()`. See also the source files in our kit for details.

4.3.6. Number of Partitions

The number of partitions of `twomass_xyzi` is an important factor for performance. A public version of 2MASS PSC is provided as 92 files divided by declination.¹³ Therefore, we create $92 \times n$ partitions and test the performance of cross-identification as multiple radial searches for $n = 2$, $n = 4$, $n = 8$, and $n = 16$. Figure 5 is the result of the test. All measurements were made with enough cached data in the main memory. The case of $n = 8$ shows significant improvement compared with $n = 2$ or $n = 4$. However, the $n = 16$ case of radius = 0.25' exhibits a slight decrease of the performance. We suspect that increasing the UNION ALL phrase in $n = 16$ case causes the slowdown and that around $n = 8$ might be the best number of partitions.

¹³ Strictly speaking, the neighboring two files have some overlapped area in declination. We have to be careful in the area when selecting objects with strict declination ranges.

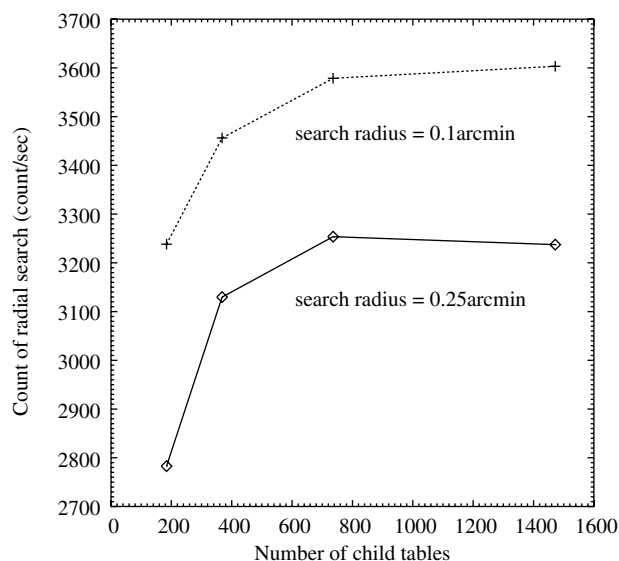


FIG. 5.—Performance of cross-identification between all objects of AKARI/IRC PSC and all objects of 2MASS PSC for different numbers of partitions of 2MASS PSC. The count of radial search per second is plotted against the number of child tables of 2MASS PSC. Hardware is a 2× Opteron2384 CPU on a Supermicro dual-processor board with 64 Gbyte memory.

As a result, we apply $n = 8$ for our system, which achieves comparable performance with the case of 5 million objects in Figure 3.

4.4. Performance with a Standard PC

We test the performance of a radial search of 2MASS PSC using a standard personal computer. Table 2 is the test results, including four cases of different search radii, and shows satisfactory performance. This test is made in the “psql” interactive terminal with the following SQL statement:

```

SELECT count(*)
FROM fTwomassGetNearbyObjEq(0, 0, radius);

```

after the `\timing` command. All measurements were made with enough cached data in the main memory; therefore, the

TABLE 2
PERFORMANCE OF RADIAL SEARCH AND RECTANGULAR SEARCH OF 2MASS PSC

Search criteria	No. Objects	Elapsed time
Radial ($r = 1'$)	2	0.001 s
Radial ($r = 60'$)	5198	0.022 s
Radial ($r = 180'$)	47632	0.149 s
Radial ($r = 360'$)	189784	0.484 s
Rectangular ($2^\circ \times 2^\circ$)	6644	0.025 s
Rectangular ($10^\circ \times 10^\circ$)	167266	0.386 s

NOTE.—Hardware is a Core2Quad Q9650 (3.0 GHz) CPU on GIGABYTE GA-EX38-DS4 with 8 Gbyte DDR2-800 memory.

actual search speed may be slower than them, due to the bottleneck of disk I/O. This bottleneck is generally reduced by performing many searches for a long span that increases memory cache efficiency.

In actual searches, we use this stored function and natural join between returned result and `twomass` table:

```
SELECT o.ra,o.dec,o.j_m,o.h_m,o.k_m,
       o.j_msigcom,o.h_msigcom,o.k_msigcom,
       n.distance
FROM fTwomassGetNearbyObjEq(0,0,3) n, twomass o
WHERE n.objid = o.objid;
```

where a join on the primary key `n.objid = o.objid` works fast enough. See the document of our software kit for details.

5. TECHNICAL DESIGN OF RECTANGULAR SEARCH

As shown in Figure 4, we implement rectangular search using an approach similar to that of radial search. Rectangular search is used as a one-time search in major cases; therefore, we implement it so that we can obtain better performance with minimum cost. Although we introduced the CE feature of PostgreSQL in §§ 3 and 4.3.5, we did not use it for radial search. On the other hand, we found that CE is suitable for rectangular search, and it simplifies our implementation.

We create 92 partitions (child tables) for rectangular search following the recommendation (less than 100 partitions) of the official document of PostgreSQL, and we distribute all rows into child tables divided by their declination. Then we create indices on all the child tables. Here is an example to create one pair of indices:

```
CREATE INDEX twomass_j2000i_aaa_radeci
ON twomass_j2000i_aaa (rai,dec);
CREATE INDEX twomass_j2000i_aaa_decrai
ON twomass_j2000i_aaa (dec,rai);
```

where `twomass_j2000i_aaa` is the name of a child table. After creating a stored function for a rectangular search in PL/pgSQL, we can run a fast rectangular search like this:

```
SELECT o.ra,o.dec,o.j_m,o.h_m,o.k_m,
       o.j_msigcom,o.h_msigcom,o.k_msigcom
FROM fTwomassGetObjFromRectEq(0,0.1, 1,1.1) n,
twomass o
WHERE n.objid = o.objid;
```

Note that we have to write the code of the stored function `fTwomassGetObjFromRectEq()` in PL/pgSQL, since a search must be performed as dynamic SQL execution. A stored function written in SQL only supports static SQL execution, under which CE does not work.

Table 2 includes the performance of two cases of rectangular search. On average, the search speed with CE and partitioning is

faster by more than 10 times compared with the searches using an index on a single table.

Our stored function for rectangular search has several other minor contrivances. See the document and source files in the 2MASS Kit for details.

6. SUMMARY

We develop a software kit to construct a high-performance astronomical catalog database supporting 2MASS PSC and several all-sky catalogs on a standard personal computer. The kit has a document that includes step-by-step instructions for installation and a tutorial for database beginners, and it utilizes open-source RDBMS. Therefore, any users can easily build their own catalog server without software licensing fees and can search the catalogs with various criteria using SQL.

Our kit is tuned for optimal performance of positional search, i.e., radial search and rectangular search. We use an orthogonal coordinate system for database index to implement the radial search that is most important in the positional search. This *xyz*-based method needs neither special processing for polar singularity nor spatial splitting such as HTM or HEALPix. Therefore, we can develop cost-effective astronomical database systems.

The implementation of radial search for relatively small (less than several million entries) catalogs can be very simple, and good performance is realized. We also show that such simple implementation is not enough for the severe search requirements of huge catalogs, and we need additional techniques. We examine our revised implementation of radial search of the 2MASS PSC using techniques of table partitioning, composite expression index, stored functions, etc. Our performance tests of cross-identification of *AKARI*/IRC PSC (870,973 objects) with 2MASS PSC (470,992,970 objects) achieve about a 2000 counts s⁻¹ radial search using a dual-processor server. Additional tests using a standard personal computer also show satisfactory performance of radial search with some typical search radii.

We also present our simple implementation of fast rectangular search for which the constraint-exclusion (CE) feature of PostgreSQL works effectively to improve performance.

Commercial RDBMS products have often been used for services for huge catalogs. Our report shows that an open-source RDBMS product is also a good choice to develop astronomical database services.

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Appendix A

STORED FUNCTIONS IN § 4.2

Here, we explain each stored function in the definition of the `fAkariIrcGetNearestObjIDEq()` function in § 4.2. All stored functions shown next are written in C.

1. `fEq2X(ra,dec)`, `fEq2Y(ra,dec)`, and `fEq2Z(ra,dec)` convert J2000 (ra,dec) to (cx, cy, cz) of the unit vectors, respectively.

2. `fDistanceArcMinXYZ(cx1,cy1,cz1,cx2,cy2,cz2)` returns the angular distance (in arcminutes) between two positions, $(cx1,cy1,cz1)$ and $(cx2,cy2,cz2)$.

3. `fArcMin2Rad(distance)` converts the distance in arcminutes to radians.

Appendix B

PERFORMANCE TUNING

Throughout the tests of cross-identification presented in this article, we use PostgreSQL 8.4.5 with CentOS 5.5 64 bit on x86_64 compatible hardware. We have adjusted the following points to obtain the highest performance for our hardware:

1. Dynamic clocking of the CPU and others are disabled. We stop `cpuspeed` using the `chkconfig` command in OS and

turn off C1E (Enhanced Halt) in BIOS. If they are enabled, the performance may decrease by more than 10%.

2. We set the `readahead` parameter to 1024 using the `hdparm` command. This sometimes improves by several percent compared with the default value.

3. We set the `noatime` option of the `mount` command for database storage.

Appendix C

CROSS-IDENTIFICATION USING SSD AND MULTICORE CPU

One of the best methods to perform cross-identification with huge catalogs is the plane sweep techniques (Devereux et al. 2005; N. Hambly 2011, private communication). Although 2MASS Kit supports cross-identification as multiple radial searches, such a RDBMS-based approach might generally be unsuitable for the best performance. However, we found that satisfactory performance can be obtained using 2MASS Kit with recent inexpensive and high-speed SSDs and multicore CPUs.

We store the PostgreSQL database files of the index set and table set for radial search (about 30 Gbyte) into a Crucial C300 MLC SSD, and we test the performance of cross-identification between AKARI/IRC PSC and 2MASS PSC using six-core (12-thread) CPUs on a dual-processor board. We connect multiple sessions to the PostgreSQL server and execute the following SQL statements simultaneously:

```
SELECT count(
  fTwomassGetNearestObjIDEq(o.ra,o.dec,0.25))
FROM ( SELECT * FROM AkariIrc
  WHERE objid % n = m ORDER BY dec ) o;
```

where n is the number of sessions, and a unique sequential number beginning with 0 is assigned to m for each session.

For example, we set $n = 4$ and $m = 0, 1, 2$, and 3 for cross-identification using four sessions (threads).

The results are shown in Table 3. Less than 10 sessions show significant scaling factor. Recent mainstream CPUs have four cores or more; therefore, RDBMS-based multiple radial searches might become a good choice for several situations.

TABLE 3
RESULTS OF MATCH-UP OF AKARI/IRC PSC WITH
2MASS PSC USING MULTIPLE RADIAL
SEARCHES WITH MULTIPLE SESSIONS

Sessions	Elapsed time	No. radial searches
1	7.72 minutes	1881 counts s ⁻¹
2	4.55 minutes	3189 counts s ⁻¹
4	2.50 minutes	5796 counts s ⁻¹
8	1.50 minutes	9697 counts s ⁻¹
10	1.35 minutes	10741 counts s ⁻¹
12	1.28 minutes	11333 counts s ⁻¹
18	1.22 minutes	11902 counts s ⁻¹
24	1.22 minutes	11898 counts s ⁻¹

NOTE.—Hardware is 2× XEON X5650 (2.67 GHz, six-core, 12-thread) CPU on a Supermicro dual-processor board and LSI 9211-4i HBA with a Crucial C300 SSD.

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