THE CATS SERVICE: AN ASTROPHYSICAL RESEARCH TOOL

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ABSTRACT

We describe the current status of CATS (astrophysical CATalogs Support system), a publicly accessible tool maintained at Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) (http://cats.sao.ru) allowing one to search hundreds of catalogs of astronomical objects discovered all along the electromagnetic spectrum. Our emphasis is mainly on catalogs of radio continuum sources observed from 10 MHz to 245 GHz, and secondly on catalogs of objects such as radio and active stars, X-ray binaries, planetary nebulae, HII regions, supernova remnants, pulsars, nearby and radio galaxies, AGN and quasars. CATS also includes the catalogs from the largest extragalactic surveys with non-radio waves. In 2008 CATS comprised a total of about 10^9 records from over 400 catalogs in the radio, IR, optical and X-ray windows, including most source catalogs deriving from observations with the Russian radio telescope RATAN-600. CATS offers several search tools through different ways of access, e.g. via Web-interface and e-mail. Since its creation in 1997 CATS has managed about 10^5 requests. Currently CATS is used by external users about 1500 times per day and since its opening to the public in 1997 has received about 4000 requests for its selection and matching tasks.

Keywords: Astronomical databases, Catalogs - radio astronomy, Radio sources

1   INTRODUCTION

Vast amounts of astrophysical information are now being published, based on observations of small and large sky regions. Typically, this information includes coordinates of the observed objects and their physical characteristics in the form of source catalogs. In fact, almost every new large-scale observational experiment produces a new catalog of objects. Modern astrophysics operates with source parameters obtained in different wavelength ranges with the goal of obtaining the most detailed understanding of physical properties and the processes of radiation of these objects. The ability of using different catalogs makes this problem considerably simpler.

 Over the past decades several different attempts have been made to combine large numbers of astronomical catalogs and make them accessible in a unified way, which can be classified grossly into two categories: databases of objects and catalog browsers. Examples of the former are NED (Helou et al., 1990; Mazzarella et al., 2002), Simbad (Egret, 1983; Wenger et al., 2000), and LEDA (Paturel et al., 1997). Examples of the latter are Vizier (Ochsenbein et al., 2000) and Datascope (http://heasarc.gsfc.nasa.gov/vo/).

Motivated by RATAN-600 observation requirements, problems of radio source study, and the underrepresentation of radio source catalogs in the then existing object databases, the present authors decided, in 1995, to create CATS, the astrophysical CATalogues Support system. Following the radioastronomical needs, the architecture of the operating system and the considerations expressed in the reviews by Andernach (1990, 1994, 1999), we chose to design CATS as a catalog browser rather than an object database, given that it would allow us to achieve a much better completeness in terms of the number of records, implying e.g. a more complete coverage of radio source measurements over the entire radio frequency window. We thus deliberately delayed the known problem of cross-identification of all the catalogs, as provided in NED, SIMBAD, or LEDA, to a later stage. In that sense CATS is ideally suited for the experienced researcher who is looking for the largest amount of data available, but willing and able to work out the correct cross-identifications by himself. This effort will be compensated for by more complete data than those obtained from other existing object databases.

The first steps of the creation of CATS were described by Verkhodanov and Trushkin (1994, 1995a,b), Verkhodanov et al. (1997, 2000), and Trushkin et al. (2000). CATS allows one to operate with catalogs stored in ASCII and FITS binary tables, to fit radio continuum spectra, and to calculate spectral indices obtained from different radio catalogs. This service is located on the server 'cats.sao.ru' at SAO, Russia, and currently runs on

a Dual Opteron 244 under OS Linux Fedora Core 6.

2   IMPLEMENTATION OF CATS

There are many modern databases operating with standard software that allow a user to obtain information on celestial objects, their images at different wavelengths, and the corresponding bibliographic data. The above-mentioned services like NED, SIMBAD, and LEDA are among these. Other services, which may be called "virtual telescopes," offer extractions from large, dedicated imaging surveys, such as the Sloan Digital Sky Survey (SDSS) at www.sdss.org, 2MASS at www.ipac.caltech.edu/2mass/, and SkyView at skyview.gsfc.nasa.gov make use of modern Web-technologies allowing one to select sky regions either via coordinates or object name resolvers. We developed our own simple approach, following both the RATAN-600 observational tasks for the preparation of radio source spectra, as well as users' desire to be able to select observing targets from available source catalogs.   Based on simple system commands and basic functions in C, our approach permitted us to achieve the fast speed of source selection and easy portability among different Unix-like systems. Moreover, this approach was better suited to our very limited resources as it allowed easier integration of new catalogs. We believe that our best contribution is a larger number of searchable catalogs rather than a more sophisticated search interface with less accessible data. We also wish to emphasize that we are not trying to simply duplicate other catalog browsers by using their sets of catalogs. A major fraction of these has been obtained or prepared by members of our team (see e.g. Andernach 2008), and over 100 radio source lists available from CATS are not available from VizieR.

The present data collection consists of catalogs, their descriptions, and corresponding programs operating under OS Linux. The program codes are created in the C language and translated with the GNU project C compiler. The codes are freely shared, provided they are used for non-commercial goals.

New catalogs may be added to the system in conformity with the following rules:
1) Every new catalog of objects should be placed in the UNIX directory with the same name as the catalog of objects;
2) The description of the catalog should also be placed in that directory;
3) The programs (or operating scripts) for local operations with the catalog of objects are also placed in the same directory; and
4) Brief characteristics, program names and description file of the astrophysical catalog are stored in a file named 'cats_descr'.

The following information is stored in the description file 'cats_descr'
- the name of the catalog, which coincides with the name of the UNIX directory,
- the type of the catalog (radio, optical, combined, etc.),
- frequency/wavelength range,
- minimum fluxes or magnitudes,
- equatorial or/and galactic coordinate ranges of the repective catalog,
- names of the local programs for the 'select' and 'match' functions (see Section 3.2),
- name of the document file,
- number of records in the catalog,
- the size of the beam pattern or angular resolution,
- a recalibration factor (if available) to put the flux densities on a commonly agreed flux scale, and
- a reference.

Parameters from the description file are used by the programs that process the input data, e.g., user-specified limits in coordinates and/or flux density inform the operating programs about the relevant sky zones to be searched and thus economize on processing time if a given catalog is out of the required range.

The lower level of the CATS control system includes several basic utilities:
(1) 'c_sel' selects objects with parameters within the user-specified ranges;
(2) 'c_match' looks for objects falling within a certain distance from a user-specified coordinate (a "cone search");
(3) 'cats_divide' operates with catalogs sorted by right ascension and produces an index of record numbers corresponding to a certain right ascension;
(4) 'epoch' converts the user-specified coordinates if they are provided for non-standard equinox, i.e. neither 1950.0 nor 2000.0 (proper motions are assumed to be zero);
(5) catalog coordinates stored according to the equinox as published, and user-specified coordinates are converted to that equinox;

(6) 'cats_base' controls the file of descriptions 'cats_descr' selecting characteristics of catalogs and produces input parameters for the programs 'c_sel' and 'c_match.'

For catalogs in FITS binary table format (e.g., NVSS or SDSS catalogs), special programs for the 'select' and 'match' functions were prepared.

To organize access of a local user of CATS from any directory of the OS, the operation programs that process the main CATS tasks are placed in a commonly accessible directory of the OS Linux. The control procedures 'cats_sel' and 'cats_match,' organized as shell-scripts, cover all the low-level programs and provide the interface between CATS and a local user, or requests made via HTTP or e-mail. The described method of the catalog storage facilitates the database development, its expansion with new data, and the possibility to tune the supporting programs.

CATS has its own indexing procedure 'cats_divide' for object coordinates in a catalog. The program decides where to start searching records of the input catalog from an index prepared from a right-ascension sorted list, allowing one to make efficient use of hard-disk seeking functions. To avoid problems of searching within a few degrees of the poles where recalculation from one equinox to another one is done, we process the total list of objects in these zones to find a required source. The indexing of CATS lists by declination is now under consideration.

3   THE MAIN FUNCTIONS

The following functions are currently implemented in CATS:
(1) Selection of objects from one or several catalogs by the following criteria: equatorial or galactic coordinates, flux densities, spectral indices, frequencies, names, and (for some catalogs) the type of objects. Parameters common to all catalogs (coordinates and flux density) are used in the selection.
(2) Search for counterparts of objects (selected from one or several catalogs) by coordinate matching within a box, a circle, or an ellipse.
(3) Cross-identification of different catalogs. This procedure is currently available only for local users. It uses the output from the selected zones of one catalog as input for the matching procedure on another catalog.
(4) Preparation of a file with a short description and characteristics of each catalog, printing of the total list of catalogs for the required sky areas (for local user).
(5) Plotting radio spectra of selected sources. This can be done from multi-frequency catalogs, or catalogs prepared by the CATS team from cross-identification of radio catalogs at different frequencies, or even by individual user input of frequencies and flux densities for a source (at cats.sao.ru/~satr/SP/spectrum.html). This function is realized in two procedures. The first is a Java script for data in the homogenized CATS format for single objects, accessible from the web page. The second one is suitable for object lists in the local RATAN-600 data processing system.

The result of the object selection is a datafile sorted according to different object characteristics, such as right ascension (default mode), declination or frequency. This file can either be displayed on the standard output devices or sent to the user in the following formats:
(1) The 'native' (original) format of the catalog (i.e. columns as published).
(2) Standard ("homogenized"') output format. This format is organized to be common for all the catalogs and used later for unification of data, preparation of spectra and statistical analysis. The standard FITS Table format describing data and fields of the table may be added as a header of the resulting file.

3.1   Access to CATS

Different modes of access are provided according to user requirements and CATS goals, following modern trends of software development. Thus, three main modes of on-line access to the CATS service have been prepared:
(1) Dialog mode (non-graphics) has been maintained until the present. Several scripts written in the UNIX 'shell' language have been created (Verkhodanov and Trushkin 1994). They permit one to operate with CATS' supporting programs via TCP/IP and NFS protocols in the local computer network.
(2) Hypertext access (http://cats.sao.ru) is provided to allow a user from the Internet system to operate with CATS via a hypertext transfer protocol. It allows one to execute all described operations from the Web-page.
(3) FTP access (ftp://cats.sao.ru) allows a user to obtain both the description of CATS catalogs and the catalogs themselves. Here is an example of access by anonymous FTP to the catalog WISH:

```
anonymous@ftp://cats.sao.ru
ftp>   bin
ftp>   cd pub/cats/
```

```
ftp>  cd  WISH
ftp>  get wish11.cat
ftp>  bye
```

All the catalog names are stored in a file of descriptions 'cats_descr' (ftp://cats.sao.ru/cats_descr).
(4) E-mail access allows the user to send batch requests to CATS.
One can send an e-mail with requests of matching with lists or selection by several parameters. The e-mail will be read automatically and sent for execution to the CATS scripts. The result will be sent back automatically to the user via e-mail.

3.2   'Select' and `match' procedures

Two main procedures of data selection have been provided at different levels of CATS control: the 'select' and 'match' tasks. They follow the first three main functions described above and are realized in different access modes. As was described earlier, the two low-level procedures 'c_sel' and c_match' provide information according to the corresponding user requests and pass it to the upper-level control scripts 'cats_sel' and 'cats_match.' Using these two procedures, the cross-identification of catalogs is possible by using output from the `select'-function of the first complete catalog as the input of the `match'-function of the second catalog or catalogs.

3.3   E-mail access

In order to economize user's real time and avoid delays in on-line data exchange, we provide the possibility to submit a batch task in the form of an e-mail letter. The e-mail requests may have several formats (as explained in a file that is returned on an empty e-mail to cats@sao.ru, with no subject). Two examples of the body of an e-mail (no subject required) are shown below.
(1) selection task:

```
mail -s "" cats@sao.ru
    cats select
    ra min=10:30 max=10:40:00.
    dec > 10' < 12' 30"
    flux > 0.5mJy
    catalogs r epoch=1950
    cats end
```

(2) matching task:

```
mail -s "" cats@sao.ru
    cats match
    catalogs NVSS,FIRST
    window box x=30" y=10'
    sources:
    s1 02:02:00    +31:23:16    1950
    s2 02:23:10     34:03:00    1950
    s3 21:26:33.9  -18:34:33.0 1950
    cats end
```

These examples demonstrate the use of some keywords for batch requests. The beginning and end of the requests are defined by the statements: 'cats start' and 'cats end'. The first example shows how to search within certain limits of coordinates by using the 'min, max' or '<', '>' operators for right ascension 'ra' and declination 'dec'. The keywords expression 'catalogs r' sets the type of catalogs to be used for selection, where 'r' means all the radio catalogs. Instead of 'r', one may choose 'o' for the optical catalogs, 'x' for the X-ray ones, 'ir' for the infrared ones, or just the names of used lists separated with comma, e.g. 'catalogs NVSS,FIRST,WISH' (the full list of the CATS catalogs can be obtained from the CATS Web-page http://cats.sao.ru/doc/CATS_list.html). The keyword 'epoch' sets the equinox of the input coordinates. 'Flux' sets flux limits.

The second example of the e-mail task is the matching procedure. There are some additional keywords 'window box x=30" y=10', where 'box' is the type of matching window (others are 'circle' and 'ellipse'), 'x' and 'y' are along longitude   and latitude of the corresponding coordinate system, respectively. Note that 'x' and 'y' are half the side lengths of the search 'box,' the value following the 'circle' keyword is its radius, and those following the 'ellipse' keyword are the semi-major and semi-minor axes of the ellipse.

4   THE MAIN CATALOGS

The major source of the radio catalogs in CATS is the collection one of us (Andernach, 1990, 1999), who has spent considerable effort to recover older source lists not previously available in electronic form, using a scanner and optical character recognition software (Andernach, 2009). This collection is complemented in several ways: contributions from authors, astro-ph preprints, tables from electronic journals and the CDS catalog archive, as well as occasional manual retyping of the original catalog. About 70 catalogs have been typed and/or corrected manually at SAO RAS by S.Trushkin. The largest catalogs (e.g. NVSS, FIRST, SDSS, etc.) were copied from Web-sites of the catalog authors.

CATS is mainly a radio-astronomical catalog service. All major catalogs incorporated into CATS are shown in Tables 1 (adapted and updated from Table 1 of Andernach, 1999) and 2.

Table 1. Major radio astronomical catalogs available in CATS

Freq. (MHz)	Name	Year of Publ.	RA(h) I(d)	Dec(degr) B(d)	Beam Width (arcmin)	min F.D. (mJy)	Number Objects
10-25	UTR-2	78-02	0-24	$>$-13	25..60	10000	1754
38	8C	90/95	0-24	$>$+60	4.5	1000	5859
74	VLSS	2004	0-24	>-30	1.3	350	32521
80	CUL1	73	0-24	-48,+35	3.7	2000	999
80	CUL2	75	0-24	-48,+35	3.7	2000	1748
82	IPS	87	0-24	-10,+83	27x350	500	1789
151	6CI	85	0-24	<+80	4.5	200	1761
151	6CII	88	8.5-17.5	+30,+51	4.5	200	8278
151	6CIII	90	5.5-18.3	+48,+68	4.5	200	8749
151	6CIV	91	0-24	+67,+82	4.5	200	5421
151	6CVa	93	1.6-6.2	+48,+68	4.5	~300	2229
151	6CVb	93	17.3-20.4	+48,+68	4.5	~300	1229
151	6CVI	93	22.6-9.1	+30,+51	4.5	~300	6752
151	7CI	90	(10.5+41)	(6.5+45)	1.2	80	4723
151	7CII	95	15-19	+54,+76	1.2	~100	2702
151	7CIII	96	9-16	+20,+35	1.2	~150	5526
160	CUL3	77	0-24	-48,+35	1.9	1200	2045
178	4C	65	0-24	-7,+80	15x7.5	2000	4844
232	MIYUN	96	0-24	+30,+90	3.8	~100	34426
325	WENSS	98	0-24	+30,+90	0.9	18	229420
327	WSRT	91	5 fields	(+40,+72)	~1.0	3	4157
352	WISH	2002	0-24	-25,-9	0.9	18	90357
365	TXS	96	0-24	-35.5,+71.5	~.1	250	66841
408	MRC	81/91	0-24	-85,+18.5	~3	700	12141
408	B2	70-73	0-24	+24,+40	3x10	250	9929
408	B3	85	0-24	+37,+47	3x5	100	13354
608	WSRT	91	sev.fields	(~40,~72)	0.5	3	1693
611	NAIC	75	22-13	-3,+19	12.6	350	3122
843	SUMSS	99	0-24	<-30	0.72	6	178975
1400	GB	72	7-16	+46,+52	10x11	90	1086
1400	GB2	78	7-17	+32,+40	10x11	90	2022
1400	WB92	92	0-24	-5,+82	10x11	~150	31524
1400	NVSS	98	0-24	-40,+90	0.9	2.0	1810668
1400	FIRST	98	7.3,17.4	22.2,57.6	0.1	1.0	811117
		98	21.3,3.3	-11.5,+1.6			
1400	PDF	98	1.1-1.3	-46,-45	0.1-0.2	0.1	1079
1500	VLANEP	94	17.4,18.5	63.6,70.4	0.25	0.5	2436
2700	PKS	(90)	0-24	-90,+27	~8	50	8264
3900	Z	89	0-24	0,+14	1.2x52	50	8503
3900	RC	91/93	0-24	4.5,5.5	1.2x52	4	1189
3900	Z2	95	0-24	0,+14	1.2x52	40	2943
4850	MG1-4	86-91	var.	0,+39	~3.5	50	24180
4850	87GB	91	0-24	0,+75	~3.5	25	54579

4850	GB6	96	0-24	0,+75	~3.5	18	75162
4850	PMNM	94	0-24	-88,-37	4.9	25	15045
4850	PMN-S	94	0-24	-87.5,-37	4.2	20	23277
4850	PMN-T	94	0-24	-29,-9.5	4.2	42	13363
4850	PMN-E	95	0-24	-9.5,+10	4.2	42	11774
4850	PMN-Z	96	0-24	-37,-29	4.2	70	2400
31	NEK	88	350<l<250	|b|<2.5	13x11	4000	703
151	7C(G)	98	80<l<180	|b|<5.5	1.2	~100	6262
327	WSRTGP	96	43<l<91	|b|<1.6	~1.0	~10	3984
1400	GPSR	90	20<l<120	|b|<0.8	0.08	25	1992
1408	RRF	90	357<l<95.5	|b|<4.0	9.4	98	884
1420	RRF	98	95.5<l<240	-4<b<5	9.4	80	1830
1400	GPSR	92	350<l<40	|b|<1.8	0.08	25	1457
2700	F3R	90	357<l<240	|b|<5	4.3	40	6483
4875	ADP79	79	357<l<60	|b|<1	2.6	~120	1186
5000	GT	86	40<l<220	|b|<2	2.8	70	1274
5000	GPSR	94	350<l<40	|b|<0.4	~0.07	3	1272
5000	GPSR	79	190<l<40	|b|<2	4.1	260	915

Table 2. Some catalogs of other wavelength ranges in the CATS

lambda	Name	Publ	RA	Dec	Number
opt	PGC	89	0-24	-90,+90	73197
opt	MCG	75	0-24	-33.5,+90	31886
opt	MSL	85	0-24	-90,+90	181603
opt	SDSS	DR6	2007	Several fields	Gals: 216906
					QSOs: 22033
ir	IRASPSC	87	0-24	-90,+90	245889
ir	IRASFSC	89	0-24	|b|>10	235935
ir	IRASSSC	89	0-24	-90,+90	43886
ir	2MASS	2000	0-24	-90,+90	470992970
Xray	ROSAT	95	0-24	-90,+90	74301
mix	QSO HB2	93	0-24	-84,+86	7315
mix	VERON+11	93	0-24	-83,+85	48921

CATS also contains observational and combined catalogs of various Galactic and extragalactic objects unified in the combined tables described in Verkhodanov et al. (2005) where the references to all the mentioned catalogs can be found.

5   SUMMARY

CATS provides a simple and convenient access to astrophysical data and complements the data available from other services, most notably for radio continuum flux densities, for which it provides the largest amount of data in any such service. Operation with CATS permits astronomers to search for peculiar objects and study physical processes in sources of cosmic radiation.

Until October 2004, we registered over 28000 requests for the 'select' or 'match' procedures, which are the most popular. The most popular catalogs for FTP-copying over the last five years are QSO by Hewitt and Burbidge (20 times), PGC (19 times), and NVSS (18 times). CATS processes daily up to 1000 HTTP-requests for information concerning the catalog descriptions.

CATS is being expanded continuously and presently comprises more than 400 catalogs including all the RATAN-600 catalogs. In its present form CATS occupies about 60Gb of disk space, which makes its installation possible also on notebooks. One of the possible future developments of the system is the preparation of the VOTable format for output tables. At present, limited resources preclude linkage with the Virtual Observatory (VO).

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