A VLBI Survey at 2.29 GHz

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The Deep Space Network is establishing a high-accuracy VLBI celestial reference frame. This article presents the results of a search for suitable radio sources to be used in constructing this frame. The VLBI observations using DSN baselines at 2.29 GHz with fringe spacings of about 3 milliarcseconds have been performed on 1398 radio sources spread over the entire sky. Of those, 917 sources were detected including 93% of the identified BL Lacertae objects, 86% of Quasars and 36% of galaxies. The resulting catalog of compact radio sources is also useful for various astrophysical studies and in the formation of VLBI celestial reference frames.

I. Introduction

This article presents the results of a systematic VLBI full-sky survey undertaken to establish a comprehensive catalog of ultracompact celestial radio sources. The survey was conducted by performing 2.29 GHz VLBI observations on known radio sources to search for compact structure. Of 1398 radio sources observed, 917 sources have been detected. Arcsecond positions for 787 of the detected sources have been previously determined from the VLBI survey data (Refs. 1, 2, 3) and are being used to identify optical counterparts (Refs. 4, 5, 6).

The results of this survey are presently being utilized to form a VLBI reference frame of 100–200 sources by determining precise relative positions ($0\overset{''}{.}01 - 0\overset{''}{.}01$) (see Ref. 7). Such celestial reference frames (see also Ref. 8) will be at least an order of magnitude more precise than previous stellar frames and are nearly inertial since the extragalactic sources are without measurable proper motions. They enable significant advances in various geodetic and astrometric studies (e.g., crustal plate dynamics, earth rotational irregularities, planetary dynamics, interplanetary spacecraft navigation). A similar, but deeper, VLBI survey of the ecliptic zone has been previously published (Ref. 9).

The VLBI survey is also useful for studying the characteristics of compact radio sources. The detected survey sources coincide with the cores of quasars and galaxies. Understanding the nature of these energetic cores is crucial in unraveling the origin and evolution of the objects in which they reside. The catalog will not only serve as a reference list for observers, but it can be used in statistical studies of radio source properties and cosmological theories. Toward these ends, the catalog has been supplemented with optical identifications, optical magnitudes, redshifts and radio spectral indices derived from the literature.

II. Sample Selection and Completeness

Candidate sources were selected primarily from the Parkes survey (Ref. 10) and the NRAO-Bonn survey (Ref. 11) which together span the entire sky ($|b^{II}| > 10$ degrees). These surveys both provide total flux density measurements at 2.7 and 5.0 GHz for most sources. The sample observed with VLBI covers the full sky and was chosen largely on the basis of criteria placed on total flux density $S(S_{2.7})$ and spectral index $\alpha(\alpha_{2.7}^{5.0}; S \equiv S_o f^{\alpha})$, neglecting temporal variability. For example, for those sources for which the Parkes and NRAO-Bonn surveys give total flux densities at both 2.7 and 5.0 GHz, 100% of the sources were observed for which $S \geqslant 1.0$ Jy and $\alpha \geqslant 0.0$ (114 sources observed, 105 detected), and 89% for which $S \geqslant 0.5$ Jy and $\alpha \geqslant -0.5$ (717 of 805 sources observed, 592 detected).

Also observed were 681 weaker or steeper spectrum sources from the Parkes and NRAO-Bonn surveys, as well as from the general literature. Our sample was intended to be purely extragalactic, and identified galactic sources were eliminated from the sample. However, some of the optically unidentified sources that met our sample criteria could be galactic. Such sources are highly unlikely to have been detected with VLBI at our angular resolution and sensitivity.

Completeness of the observed sample is difficult to estimate, not only due to temporal variability but also because the two finding surveys had different levels of completeness for different sky regions, lacked two frequency information for all sources, and had different primary survey frequencies. Neglecting temporal variability, both finding surveys are nearly complete for $S \geqslant 1.0$ Jy and $\alpha \geqslant -0.5$, resulting in a combined completeness of more than 97% for the sky area covered. The spectral index criterion is necessary because the NRAO-Bonn survey frequency was 5.0 GHz, not 2.7 GHz. Based on these sample criteria, the VLBI survey is estimated to be 93% complete, again neglecting temporal variability, with a total of 312 sources observed. Because the flux density limits of the finding surveys varied depending on sky region, estimates of completeness for sources with lower total flux densities do not apply to the entire sky (see Table 1).

III. The Observations

The observations were performed at 2.29 GHz with pairs of antennas on California-Spain, California-Australia, and Australia-South Africa baselines (see Table 2) during 68 different observing sessions between 1974 and 1983 (see Table 3). Right circular polarization was received and data were recorded on the NRAO Mark II system (Ref. 12).

The fringe spacing sampled ranged from 2.5 to 4.1 milliarcseconds. For the mean fringe spacing of 3.3 milliarcseconds, the normalized fringe visibility of a Gaussian source varies from 0.9 to 0.1 as the half-intensity diameter increases from 0.5 to 2.2 milliarcseconds.

The 5σ detection limit in correlated flux density was generally ~0.1 Jy. The corresponding random uncertainty in detected source strength is ~0.02 Jy, but systematic errors at about the 10% level dominate the random contribution for most sources. To ensure that few compact radio components would be missed due to a priori source position errors, the sky was completely searched within 0.5 arcminutes of all nominal source positions by cross-correlating over an appropriate range of delay and delay rate.

Total flux densities at 2.29 GHz were also measured for most sources at the time of VLBI measurement by means of on-off measurements with a noise-adding radiometer. The random uncertainties in total flux density measurements typically range from 0.03 to 0.3 Jy, with systematic errors in antenna sensitivity being ~3%.

IV. Results

Of 1398 sources observed, 917 (or 66%) were detected with VLBI; 83% of the observed sources with $S \geqslant 0.5$ Jy and $\alpha \geqslant -0.5$ were detected. Figure 1 is an equal area sky distribution plot of the detected objects. Sparsity near the galactic plane is evident. Figure 2 is a correlated flux density histogram of the detected objects. There are 49 sources with correlated flux densities greater than 1 Jansky, and 227 sources with correlated flux densities greater than 0.5 Jansky.

Detection statistics as a function of optical identification type appear in Table 4. Detection statistics as a function of general optical class appear in Table 5: 93% of identified BL Lacertae objects were detected, 86% of QSOs were detected and 36% of galaxies were detected.

Figure 3 displays a sample page of the survey results. Figure 4 displays a sample page of the reference table to the supplementary data given in Fig. 3. Figures 3 and 4 will appear in their entirety in a separate report. Descriptions of the entries to Fig. 3 appear below.

Column	Description
1	Source name
2/3	1950.0 positions. Asterisked positions are determined from the VLBI survey data and have typical uncertainties of 1 arcsecond (see Refs. 1-3). Other

Column	Description
	positions are from the literature, and in most cases, errors are < 30 arcseconds.
4	Spectral indices between 2700 to 5000 MHz followed by corresponding reference number (see Fig. 4). A few existing compilations of redshifts, optical identifications and optical magnitudes were useful aids in preparing our catalog (Refs. 63, 84, 86, 111 and 232 in Fig. 4). However, in almost all cases we have drawn values for these quantities from original references to enhance accuracy. A star following the reference number indicates a questionable or conflicting value, and is explained in the notes to Fig. 3. For many Southern Hemisphere sources, the optical characteristics were obtained from an optical identification program which utilized the radio source positions determined by our survey (Refs. 4, 5, 6).
5	Redshifts followed by corresponding reference number (see Fig. 4).
6	Optical identifications followed by correponding reference number (see Fig. 4). Optical identification codes are defined in Table 4.
7	Optical magnitudes followed by the corresponding reference number (see Fig. 4). These values may be visual, blue or red.
8	Experiment codes as defined in Table 3.
9	Measured 2.29 GHz total flux density (Jansky).
10	Measured 2.29 GHz correlated flux density (Jansky). Values for 17 ecliptic sources marked by asterisks are from Ref. 9.
11	Visibility is defined as the correlated flux density divided by the total flux density.
12	East-west (u) and north-south (v) spatial frequencies of the observations in units of 10^6 wavelengths.

Computer readable versions of the catalog are available upon request.

Acknowledgments

We are indebted to the instrumentation and observing assistance supplied by L. J. Skjerve, D. J. Spitzmesser, and the operations personnel of the Deep Space Network, the Australian National Radio Observatory at Parkes, Australia, and the Hartebeesthoek Radio Astronomy Observatory, South Africa. We are also grateful to A. W. Harris, E. Padua, M. A. Slade, G. B. Trager and J. Kidder for computational aid.

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Table 1. Completeness estimates for various sample criteria

Declination Range, deg	Flux Density Limit ($S_{2.7}$), Jy	Spectral Index Limit ($\alpha^{5.0}_{2.7}$)	Number of Sources Observed*	Number of Sources Detected*	Completeness of Sample, %
−90 to +90	⩾ 1.0	⩾ −0.5	312	258	93
−90 to +27	⩾ 0.65	⩾ −0.5	396	336	85
+70 to +90	⩾ 0.5	⩾ −0.5	30	29	97

*Includes small adjustment to account for estimated number of sources with total flux density given at only one frequency which would have $\alpha > -0.5$.

Table 2. Participating observatories

Location	Designation	Diameter, m	Baseline Length: Kilometers $\times 10^3$	Baseline Length: Wavelengths $\times 10^6$
Hartebeesthoek, S. Africa	HT	26		
			9.7	75
Parkes, Australia	PK	64		
Tidbinbilla, Australia	43	64		
	42	26		
			10.6	81
Goldstone, California	14	64		
	13	26		
			8.4	64
Madrid, Spain	63	64		
	61	26		

Table 3. Experiment summary

Experiment Code	Date YR	MN	DY	Observatories	Experiment Code	Date YR	MN	DY	Observatories
1	74	07	31	14 42	35	78	03	05	13 63
2	74	08	13	14 42	36	78	03	14/15	13 63
3	75	06	17	14 42	37	78	03	21	13 63
4	75	06	18	14 42	38	78	04	04	13 63
5	75	08	23/24	14 42	39	78	04	16	13 43
6	75	08	23	14 62	40	78	05	30/31	13 43
7	75	09	15	14 42	41	78	06	29/30	13 43
8	75	09	21	13 63	42	78	10	18	13 43
9	75	10	26	13 43	43	80	2	1	14 43
10	76	05	27	14 63	44	80	2	27/28	14 43
11	76	11	09/10	13 63	45	80	3	2	13 43
12	76	11	11	13 63	46	80	3	3	13 63
13	76	11	14	13 43	47	80	3	12/13	13 63
14	77	01	28	13 43	48	80	3	14/15	13 63
15	77	02	12	13 43	49	80	3	19	13 43
16	77	02	20	13 43	50	80	3	26	13 43
17	77	02	21	13 43	51	80	3	27	13 63
18	77	02	23	13 43	52	80	4	24–27	PK HT
19	77	02	25	13 43	53	80	4	26	43 HT
20	77	04	21	13 43	54	80	6	19	14 43
21	77	04	22	13 43	55	81	1	21	13 43
22	77	06	15	13 43	56	81	1	25	13 43
23	77	09	11	14 61	57	81	1	31	13 43
24	77	09	28/29	13 63	58	81	3	1	14 43
25	77	10	11	13 63	59	81	4	22	14 43
26	77	10	27/28	13 43	60	81	5	8	14 43
27	77	11	01	13 43	61	81	10	23	13 43
28	77	11	21	13 43	62	81	10	26	13 43
29	77	12	02	13 43	63	81	11	1	13 43
30	77	12	11	13 43	64	82	2	14	43 HT
31	77	12	12	13 43	65	82	2	17	43 HT
32	77	12	13/14	13 43	66	82	2	19/20	43 HT
33	78	01	09/10	13 43	67	82	4	20	43 HT
34	78	02	20/21	13 43	68	83	6	21	13 43

Table 4. Optical identification codes with VLBI detection statistics

Optical ID	Description	Number of Detections	Number of Nondetections	Percent Detected
B	Blue Stellar Object	34	6	85
CG	Compact Galaxy	1	2	33
D	Diffuse Galaxy	6	9	40
DB	DB Galaxy	3	8	27
D4	D4 Galaxy	0	2	0
E	Elliptical Galaxy	10	28	26
E0	E0 Galaxy	3	4	43
E1	E1 Galaxy	1	2	33
E2	E2 Galaxy	2	2	50
E3	E3 Galaxy	1	1	50
E4	E4 Galaxy	3	2	60
E5	E5 Galaxy	0	1	0
EF	Empty Field	84	65	56
G	Galaxy	48	97	33
L	BL Lacertae Object	56	4	93
N	Neutral Stellar Object	14	3	82
NG	N-Galaxy	11	5	69
N2	Type 2 N-Galaxy	0	2	0
PG	Probable Galaxy	10	9	53
PQ	Probable QSO	41	25	62
Q	Quasi-Stellar Object	503	67	88
R	Red Stellar Object	7	1	88
S	Spiral Galaxy	0	2	0
SB	Sb Galaxy	0	1	0
SC	Sc Galaxy	0	1	0
SG	Seyfert Galaxy	2	1	67
S0	S0 Galaxy	1	1	50
U	Unidentified Object	2	3	40
(Blank)	No Information	74	127	37
	Totals	917	481	66

Table 5. Optical class VLBI detection statistics

Class	Number of Detections	Number of Nondetections	Percent Detected
Galaxies and Probable Galaxies	102	180	36
QSOs and Probable QSOs	544	92	86
BL Lacertae	56	4	93
Stellar Objects	55	10	85
Empty Fields	84	65	56
No Information and Unidentified	76	130	37
Totals	917	481	66

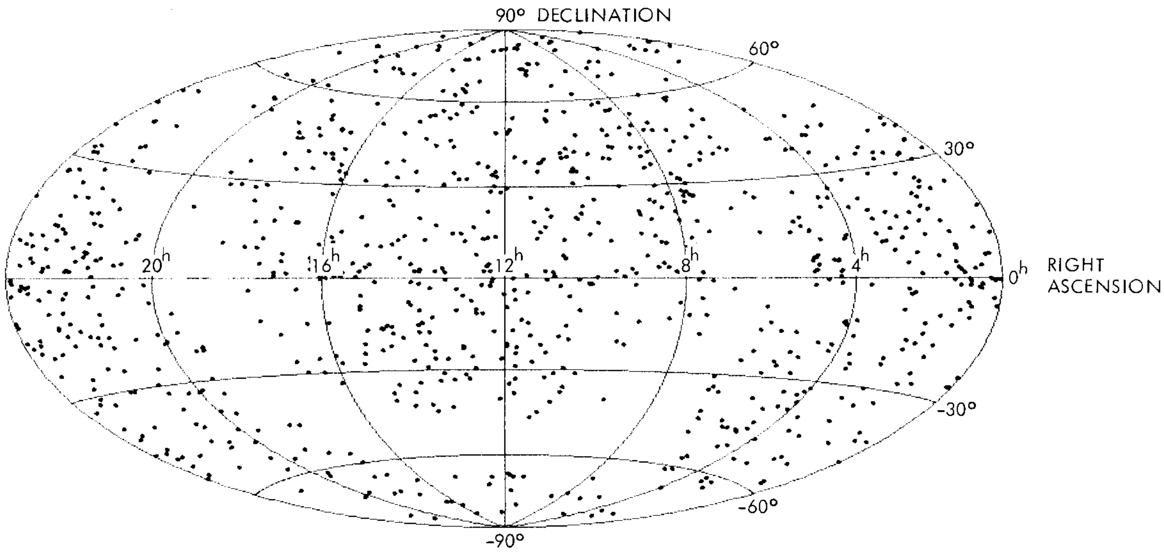

Fig. 1. Sky distribution of sources detected with VLBI

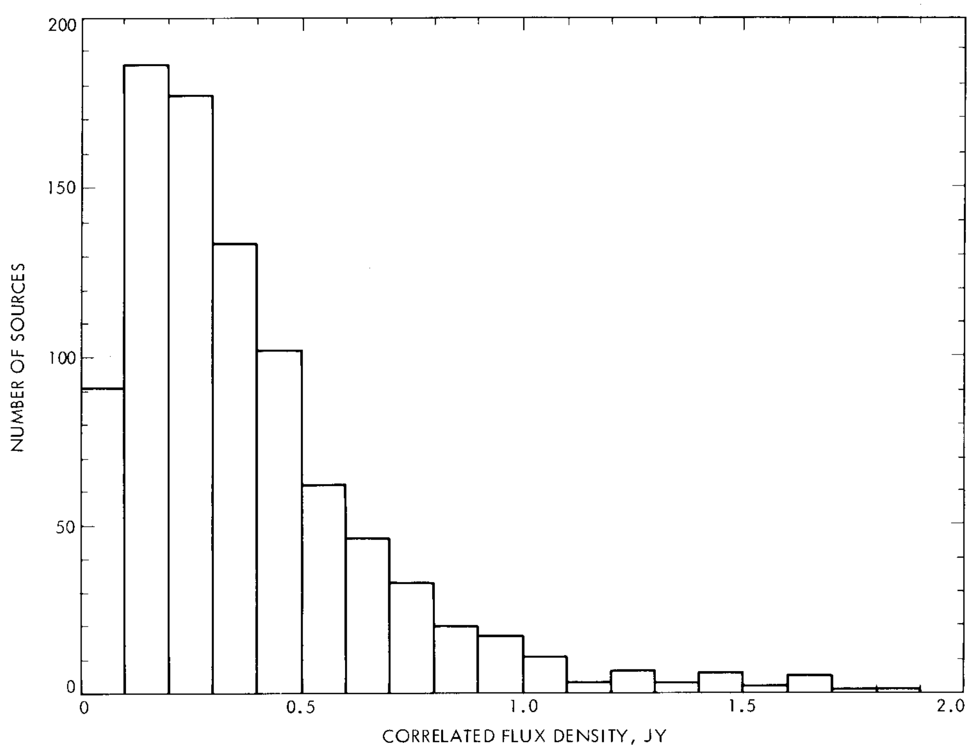

Fig. 2. Histogram of correlated flux densities for detected sources

(1) SOURCE NAME	(2) RIGHT ASCENSION HR MN SEC	(3) DECLINATION DEG MN SEC	(4) SPECTRAL INDEX	(5) RED SHIFT	(6) OPTICAL ID	(7) OPTICAL MAG	(8) EXPT CODE	(9) TOTAL FLUX DENSITY (JY)	(10) CORRELATED FLUX DENSITY (JY)	(11) VISIBILITY	(12) U (10**6 WVLNS)	V
P 0000-550	0 0 35.7	-55 1 58	-0.5 96		E 96	14.5 96	52		<0.12		-68.4	-19.2
P 0002-478	0 2 2.9	-47 53 2 *	-0.2 96		Q 174	19.0 199	52		0.49 +/-0.04		-69.9	-13.6
GC 0003+38	0 3 22.4	+38 3 33 *	-0.3 44		Q 44	19.4 13	28	0.6 +/-0.3	0.37 +/-0.04	0.6 +/-0.3	-49.9	-62.8
P 0003-56	0 3 26.6	-56 45 10	-0.8 96		G 96	19.5 96	52		<0.12		-71.3	18.1
P 0003-42	0 3 28.0	-42 52 18	-1.0 102	1.85 107	Q 103	19.5 103	52		<0.12		-71.9	14.5
NRAO 5	0 3 40.2	- 6 40 17 *	0.0 63	0.347 104*	PG 104	18.5 104	7	1.69+/-0.07	0.46 +/-0.05	0.27 +/-0.03	-58.2	-56.0
3C 2	0 3 48.8	- 0 21 6	-0.8 63	1.037 5	Q 5	19.5 5	54	2.65+/-0.07	0.062+/-0.006	0.023+/-0.002	-54.1	-56.2
P 0003-83	0 3 54.6	-83 22 22	-0.5 102		G 102	19.0 102	52		<0.12		-65.9	33.3
P 0005-239	0 5 27.5	-23 56 0 *	-0.1 39	1.407 39	Q 16	17.0 30	33		0.43 +/-0.05		-58.2	-53.0
P 0005-262	0 5 53.5	-26 15 53 *	0.0 16		G 16*	20. 16	34		0.21 +/-0.03		-51.6	-62.3
III ZW 2	0 7 57.9	+10 41 30 *		0.089 86	CG 202	15.4 202	33		0.15 +/-0.03		-57.0	-52.7
GC 0007+17	0 7 59.4	+17 7 38 *	0.4 102	1.601 30	Q 30	18.0 30	11		0.6 +/-0.1		63.5	0.8
P 0008-42	0 8 21.8	-42 9 47	-1.3 63		PG 160	22.0 160	32	3.1 +/-0.3	<0.15	< 0.048	-41.6	-69.0
P 0008-264	0 8 28.9	-26 29 15 *	+0.3 16	1.096 104	PQ 16	19. 16	34	0.58+/-0.06	0.53 +/-0.05	0.9 +/-0.1	-50.3	-63.3
P 0010+00	0 10 37.1	+ 0 35 3	-1.0 102		EF 102		54	1.08+/-0.04	<0.02	< 0.018	-54.0	-55.9
GC 0010+40	0 10 54.3	+40 34 57 *	-0.3 63		Q 115	17.9 115	38		0.34 +/-0.04		43.3	-28.2
P 0011-046	0 11 20.6	- 4 40 33 *	+1.1 79		PQ 79	19.5 79	33		0.28 +/-0.03		-58.3	-55.8
GC 0012+31	0 12 29.9	+31 59 33 *	-0.5 63		PG 80	19. 80	34	0.29+/-0.05	0.22 +/-0.03	0.8 +/-0.2	-40.5	-69.8
P 0013-00	0 13 37.4	- 0 31 53 *	-0.4 102		R 13	19.8 13	61		0.33 +/-0.02*		-57.0	-56.0
0014+81	0 14 4.5	+81 18 29 *	-0.2 63		Q 63	16.5 63	51	1.0 +/-0.3	0.35 +/-0.03	0.4 +/-0.1	-57.9	27.5
0016+73	0 16 54.1	+73 10 52	0.2 63		Q 63	18.0 63	51	1.5 +/-0.1	0.54 +/-0.04	0.36 +/-0.04	-49.2	40.3
0018+72	0 18 34.5	+72 56 4 *	-0.7 63				51	0.8 +/-0.2	0.11 +/-0.01	0.13 +/-0.04	-50.0	39.3
P 0019-00	0 19 51.7	- 0 1 42 *	-0.9 63		G 21	21.1 21	44	2.24+/-0.06	0.059+/-0.004	0.026+/-0.002	-55.9	-56.1
P 0019+058	0 19 58.3	+ 5 51 22 *	+0.2 75		L 186	19.2 186	33		0.52 +/-0.06		-57.4	-54.6
P 0022-423	0 22 15.4	-42 18 41 *	-0.8 102		EF 174		65		0.75 +/-0.04		-69.9	19.1
OB 337.7	0 22 46.7	+39 2 59 *	0.2 44		Q 44	19.8 13	24	0.7 +/-0.2	0.45 +/-0.07	0.6 +/-0.2	54.1	24.4
P 0022-60	0 22 54.4	-60 45 6	-1.1 96				65		<0.05		-70.4	19.8
P 0023-26	0 23 17.9	-26 18 45	-0.8 63		G 160	20.5 160	32	6.4 +/-0.3	<0.14	< 0.022	-51.9	-62.1
OB 338	0 24 2.8	+34 52 6 *	0.1 63		Q 45	19. 8	28	0.9 +/-0.2	0.37 +/-0.04	0.4 +/-0.1	-51.8	-61.3
P 0024-495	0 24 16.3	-49 35 21	-0.6 96		PQ 116	19.0 96	52		<0.12		-66.4	-20.7
OB 343	0 26 34.8	+34 39 58 *	-0.3 44		G 147	20.2 147	24	1.8 +/-0.2	0.16 +/-0.06	0.09 +/-0.03	57.7	18.8
P 0027+056	0 27 11.4	+ 5 38 5 *	+0.4 75		PQ 75	19.5 75	33		0.40 +/-0.05		-56.3	-54.2
0027+70	0 27 17.0	+70 21 6 *	0.0 63		EF 63		51	0.8 +/-0.1	0.21 +/-0.02	0.26 +/-0.04	-49.8	39.1
P 0028-01	0 28 58.5	- 1 17 22	-0.8 102		G 5	19.4 5	44	0.66+/-0.03	<0.02	< 0.026	-56.6	-56.4
P 0030+19	0 30 1.2	+19 37 12	0.8 102		D 102	19. 102	68		<0.10		-58.1	-54.4
P 0034-01	0 34 30.6	- 1 25 38 *	-0.8 102	0.073 21	EO 5	17.6 21	44	2.90+/-0.08	0.029+/-0.002	0.010+/-0.001	-57.4	-56.4
P 0035+23	0 35 19.8	+23 50 42 *	-0.7 102	2.27 36	PQ 200	19. 200	33		0.10 +/-0.02		-56.0	-57.8
GC 0035+12	0 35 41.9	+12 11 2 *	-0.5 63		B 32	17.0 32	33		0.14 +/-0.02		-56.6	-57.8
P 0035-02	0 35 47.2	- 2 24 9 *	-0.7 102	0.220 176	E 5	19.6 5	54	4.28+/-0.11	0.22 +/-0.01	0.052+/-0.003	-53.4	-57.0
P 0035-216	0 36 0.4	-21 36 34	0.2 16		G 16	19. 16	32	0.6 +/-0.2	<0.13	< 0.217	-49.2	-63.6
P 0035-39	0 36 2.3	-39 16 13	-1.1 102	0.592 25	Q 71	16.5 71	52		<0.12		-71.5	15.3
P 0036-62	0 36 30.0	-62 48 12	-0.9 96		E 96	18.5 96	52		<0.12		-70.7	20.6
P 0036+03	0 36 44.2	+ 3 3 25 *	-1.0 102	0.014 177	E2 5	13.5 5	54	1.38+/-0.05	0.026+/-0.002	0.019+/-0.002	-54.9	-55.0
P 0038-326	0 38 5.1	-32 41 40	0.6 73				32		<0.14		-41.7	-69.2
NB 89.01	0 38 20.0	+89 12 36					8	1.3 +/-0.2	<0.11	< 0.085	-63.8	-5.8

Fig. 3. Sample page of VLBI survey results

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Fig. 4. Sample page of references to spectral indices, red shifts, optical identifications and optical magnitudes