The Millions of Optical - Radio/X-ray Associations (MORX) Catalogue, v2

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ABSTRACT

Announcing the release v2 of the MORX (Millions of Optical-Radio/X-ray Associations) catalogue which presents probable (40%-100% likelihood) radio/X-ray associations, including double radio lobes, to optical objects. All the large radio/X-ray surveys to June 2023 are included, being VLASS, LoTSS, RACS, FIRST, NVSS, and SUMSS radio surveys and *Chandra*, *XMM-Newton*, *Swift*, and *ROSAT* X-ray surveys. The totals are 3 115 575 optical objects of all classifications (or unclassified) so associated. The catalogue is available on multiple sites.

Key words: catalogs — x-rays: general — radio continuum: general

1 INTRODUCTION

This is an update to the 2016 MORX catalogue of radio/X-ray associations onto optical objects (MORXv1: Flesch 2016), using all the largest radio and X-ray source surveys available to 30 June 2023. This update, version 2, has three times the number of optical objects so associated, and has a simpler format, just giving cumulative likelihoods and the radio/X-ray identifiers without details of their optical solutions, for ease of use. Figure 1 shows MORXv2 coverage over the sky, and explains the features seen thereon.

MORX v2 can be downloaded from NASA HEASARC[1] or CDS[2], both of which provide query pages, or from the MORX home page[3] which also provides a FITS file. Its ReadMe gives essential information about the data, and the file "MORX-references.txt" gives the legend of citations for the data. Many issues involved in the production of MORX are explained in the paper for MORXv1 (Flesch 2016), and the reader can consult there for in-depth topics. Updates and changes are as presented below, starting with a listing of the input radio/X-ray catalogues for MORX v2.

2 INPUT RADIO/X-RAY CATALOGUES

In 2016 I published the Million Optical - Radio/X-ray Associations Catalogue (MORXv1: Flesch 2016) as a quick guide to all such associations able to be calculated from the largest optical, radio, and X-ray surveys over the whole sky. That paper gives the methods used to produce this catalogue, including the optical field solutions and calculation of association likelihoods, and probabilistic classification of unclassified objects; the reader is referred there for those topics. In the seven years since, there have of course been new editions of these surveys and new such surveys published; following is the list of input radio/X-ray surveys used for MORX v2.

For radio sources there are the high-resolution VLASS, LoTSS, and FIRST surveys, the medium-resolution RACS survey, and the low-resolution NVSS and SUMSS surveys:

- The Very Large Array Sky Survey (VLASS: Gordon et al. 2020) Quick Look catalogue[4] is their first complete publication of VLASS radio sources. VLASS covers the whole sky north of declination -40° in 3GHz to a depth[5] of 1mJy and astrometric accuracy of ≈0.5 arcsec in most places. I use only their Gaussian detections with S/N≥ 4. The VLASS Quick Look detection prefix of “VLASS1QLCIR” is here shortened to "VLA" for brevity.
- The LOFAR Two-metre Sky Survey second data release (LoTSS: Shimwell et al. 2022) which is a 120-168 MHz survey which covers 27% of the Northern sky as is seen in dark on Figure 1. It has a depth of 0.5 mJy and astrometric accuracy of 0.2 arcsec, and comprises 52% of all core radio associations presented in MORX v2. LoTSS comes in two primary tables, the Source ‘island’ catalogue and the ‘Gaussian component’ (i.e., functional detections) catalogue. MORX processing is done on the detections catalogue which is architecturally many-to-one with the sources, although most sources have only the one detection. The source catalogue provides source names prefixed with ‘ILT’ (for International LOFAR Telescope), and that name is used for any MORX optically-associated detection which is the only detection for its source island. If that detection is one of many for its source island, then LoTSS does not provide a name for it, so MORX constructs the detection name with the prefix ‘ILD’ (for ILT Detection) and the J2000 of the detection location. LoTSS is the largest input catalogue and took a week for me to process.
- The Faint Images of the Radio Sky at Twenty-cm survey catalogue (FIRST: Helfand/White/Becker 2015) which is a 1.4GHz survey with a Northern-sky footprint away from the Galaxy, with a depth of 1mJy and astrometric accuracy of ≈1 arcsec.
- The Rapid ASKAP Continuum Survey (RACS: Hale et al. 2021) which is an 887.5 MHz survey which maps all sky south of

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[1] https://heasarc.gsfc.nasa.gov/W3Browse/all/morx.html
[2] https://cdsarc.cds.unistra.fr/viz-bin/cat/V/158
[3] https://quasars.org/morx.htm
[4] at https://cirada.ca/catalogues
[5] “depth” = expected 67% completeness at the given point source flux

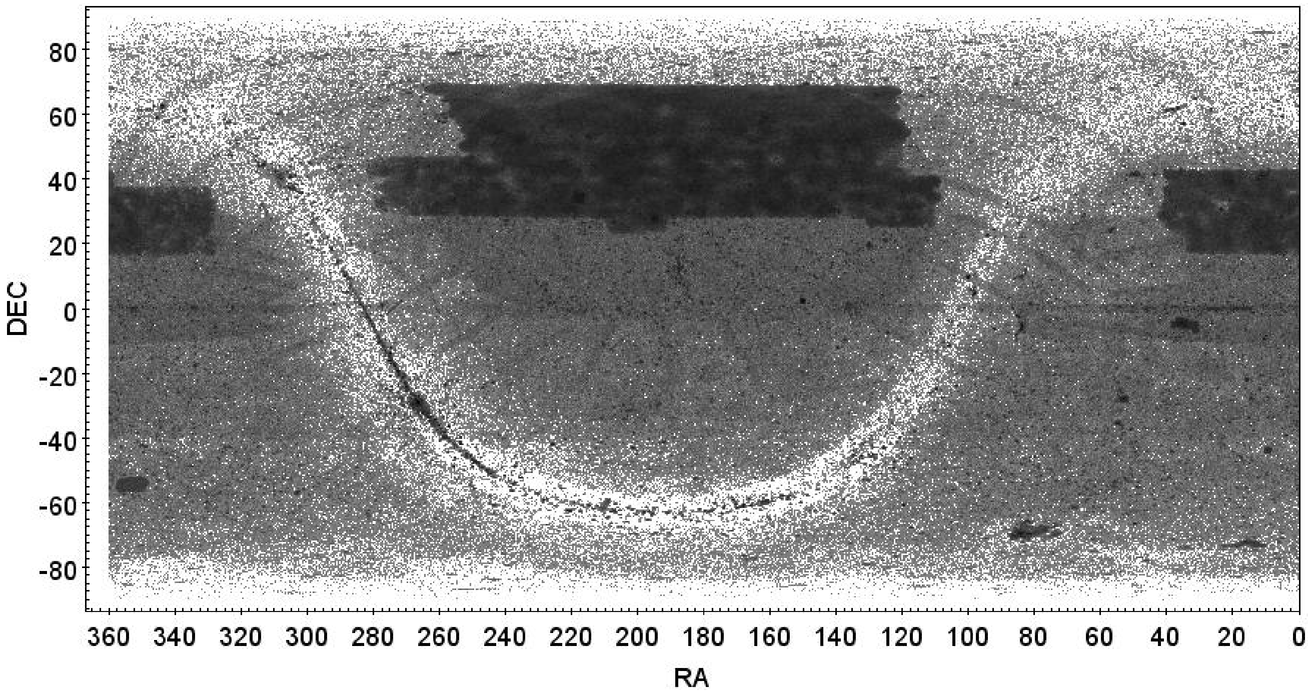

Figure 1. Sky coverage of MORX v2, darker is denser. The Galaxy winds through with X-ray stars mostly, and the Magellanic Clouds are seen at lower right. The dark footprints in the North show LoTSS radio coverage. RACS radio sources cover sky of $\delta < 30°$, NVSS radio covers sky of $\delta > -40°$, and FIRST radio covers sky of $\delta > -10°$ away from the Galaxy. X-ray source coverage is broadly uniform over the sky, following where pointed investigations were done. SDSS extensions radiate from their North sky optical coverage. The thin strip along the equator shows the deep-sky investigations there. The dense bead at lower left shows the XXL-South AAOmega X-ray field. *(chart produced with TOPCAT (Taylor 2005))*

declination +41°, although this first catalogue of sources spans only ($-80° < \delta < +30°$) for quality reasons. It has a point-source depth of 2 mJy and astrometric accuracy of ≈2 arcsec. RACS uses the same source extraction software as LoTSS, so also presents a source catalogue and a 'Gaussian' functional detections catalogue. So, as with LoTSS, MORX uses the RACS-provided source name when an optically-associated detection is the only detection for its source, and otherwise constructs a detection name with the prefix 'RACD' (for RACS Detection) and the J2000 of the detection location. I did not use the small Galaxy RACS files which cover the Galactic plane because, at the time (2021), I was doing processing for the Milliquas Quasar catalogue (Flesch 2023) only.

• The NRAO VLA Sky Survey catalogue (NVSS: Condon et al. 1998) which covers the whole sky north of declination -40° in 1.4GHz to a depth of 2.5mJy and astrometric accuracy of ≈5 arcsec.

• The Sydney University Molonglo Sky Survey catalogue (SUMSS: Murphy et al. 2007) which is analagous to NVSS but covers the sky south of declination -30° in 843MHz. It includes those associations marked as "MGPS" (Molonglo Galactic Plane survey) which is the Galactic plane component of the SUMSS survey.

X-ray surveys are collected from pointed observations by X-ray detecting satellites, so their data are not characterized by completeness and depth as are the sky-sweeping radio surveys. For X-ray sources there are 12 input catalogues from the high-resolution *Chandra* and *XMM-Newton* surveys, the medium-resolution *Swift* survey, and lower-resolution XMM-Slew and *ROSAT* satellite surveys; these are:

• For *Chandra* data, the *Chandra* ACIS source catalog (CXOG: Wang et al. 2016), the *Chandra* Source Catalog v1.1 (CXO: Evans et al. 2010) and v2.0 (2CXO: Evans et al. 2020), and the XAssist *Chandra* source list (CXOX: Ptak & Griffiths 2001a). The CXO v1.1 data is preferred over the CXO v2.0 data because CXO v1.1 provides the observation ID for each detection, needed by MORX to calculate the optical solution, whereas CXO v2.0 provides stacked detections only. *Chandra* data has the best astrometric accuracy of the X-ray surveys, but published data is only to 2014. CXO v2.1[6] will publish more recent data when released, but may provide only stacked X-ray sources aligned to optical sources which, in my view, would prejudge the identification of true sources of X-ray emission.

• For *XMM-Newton* data, catalogues used are the *XMM-Newton* DR13 (4XMM: Webb et al. 2020), the *XMM-Newton* DR3 (2XMMi: Watson et al. 2009) which gives ≈20K valid clean detections dropped by its successors (Rosen et al. 2016, Appendix D: "mostly real sources"), the XAssist *XMM-Newton* source list (XMMX: Ptak & Griffiths 2001b), and the *XMM-Newton* Slew survey release 2 (XMMSL2: Saxton et al. 2008). The Slew data is of much lower astrometric accuracy than the others, so is treated as a separate survey of low resolution in the MORX processing.

• *Swift* data is taken from the Living *Swift* X-ray Point Source catalogue (SXPS: Evans et al. 2023) as at 01-July-2023. The SXPS data are given both as observation-identified and stacked detections, so where both are present for a single source, MORX processing selects the observation-identified detections, as with the CXO processing.

• Lastly, the legacy *ROSAT* data was of a lesser astrometric accuracy; catalogues used are the High Resolution Imager (HRI: Voges et al. 1999a), Position Sensitive Proportional Counter (PSPC: Voges et al. 1999b), and the WGACAT (WGA: White/Giommi/Angelini

[6] https://asc.harvard.edu/csc2/about2.1.html

Table 1. Summary of Radio/X-ray Associations in MORX

Source Catalogue(s)	# total core associations	# primary* core associations	# double radio lobes
Radio surveys			
VLASS	439283	439283	15763
LoTSS	1804886	1710297	73142
FIRST	275552	69766	9000
RACS	582668	337540	12009
NVSS	316039	78759	675
SUMSS	47549	15891	42
total Radio Surveys	3465977	2651536	110631
X-ray Surveys			
CXOG	63503	63503	
CXO v1.1	13376	13376	
CXO v2.0	6807	6807	
CXOX	18966	18966	
total Chandra	102652	102652	
4XMM-DR13	250592	221701	
2XMM-DR3	4541	4086	
XMMX	8516	8040	
total XMM-Newton	263649	233827	
Swift LSXPS	120647	95484	
XMM Slew v2.0	11428	8778	
ROSAT HRI	11177	5146	
ROSAT PSPC	17813	12155	
ROSAT WGA	2760	2321	
total ROSAT	31750	19622	
total X-ray Surveys	530126	460363	

* For each radio source, the 'primary' association is the first occurence on this list from top to bottom, e.g., if a radio source has associations from the RACS and NVSS surveys, then RACS has the primary association because it is topmost on this list. X-ray sources are tallied similarly.

1994, May 2000 edition) which used different processing over the PSPC survey data. The *ROSAT* All-Sky Survey (RASS) is no longer used by MORX because its resolution was too coarse to yield confident optical associations in isolation.

Counts of associations from all these input catalogues are given in Table 1, plus a count of "primary associations" which are one-to-one with optical sources for each of radio and X-ray. The radio associations are calculated independently from the X-ray associations; an optical source showing both radio and X-ray associations has earned each one separately, and so can tally both as a primary radio association and a primary X-ray association in Table 1.

3 THE OPTICAL BACKGROUND USED IN MORX V2

The optical astrometry for MORX v2 hails from the "best" sources which comprise a mix of 23.7% *Gaia*-EDR3 (Lindegren et al. 2021), 46.2% Pan-STARRS (Chambers et al. 2016), 19.0% SDSS-Sweeps[7] supplemented with SDSS XDQSO (Bovy et al. 2011) optical data, 0.6% from DES (Abbott et al. 2021) or discovery authors' papers, and 10.5% from the 0.1-arcsec resolution All-Sky Portable optical catalogue (ASP: Flesch 2017) which includes legacy optical data. Most MORX objects are optically too faint for *Gaia* coverage, but SDSS is used as available, Pan-STARRS gives almost complete coverage for $\delta > -30°$, and ASP covers south of there.

By contrast, for optical photometry MORX gives only 2 bands, red and blue, so no attempt is made to give "best" values for these, as researchers will source those elsewhere, anyway. Instead, MORX presents historically-valuable calibrated POSS-I (1950's epoch) & POSS-II/UKST (1970's-1980's epoch) photometry sourced from ASP. In particular, the priority is to present POSS-I magnitudes because the blue POSS-I *O*, centred at violet 4050Å, is well-separated from the red Cousins 6400Å, and the two plates were always taken on the same night thus giving accurate red-blue colour even for variable objects. In total, MORX gives photometry comprised of 37.4% POSS-I, 26.7% POSS-II/UKST, 31.6% SDSS-Sweeps, 1.9% Pan-STARRS, 0.6% DES, and 1.9% other.

For MORX v2 (this edition), I have modified the optical field solutions documented in MORXv1, in that I have constrained the optical field shifts to be no more than 8 arcsec in each of RA and DEC. This is because of the concise presentation of this edition where each radio/X-ray association is displayed simply with its J2000-based name, without elaboration. Thus each such association needs to be "seen to be" correct, lest it be "seen to be" wrong. Thus I drop any association found to be positionally too far removed from its own J2000-based name (that name showing its original astrometry, in principle); in practice, this drops about 2% of the X-ray associations but does not disturb the radio associations. Spot checks on the removed X-ray field shifts show most were only marginally aligned to the optical background, but some were quite clear, e.g., the *ROSAT*-HRI field US700009H.N1 (centred over NGC 3628) shifted 15 arcsec which revealed X-ray emission for 5 quasars in a closely-aligned fit. However, usually such places have since been resurveyed anyway, thus clarifying the true optical sources, as in this case which was resurveyed by *Chandra* which confirmed the field-shifted HRI-found associations, and so preserving those optical sources in MORX.

4 ASSOCIATION LIKELIHOODS OF RADIO/X-RAY SOURCES

The calculations of the likelihood of core radio or X-ray associations to an optical object are as presented in MORX v1, but now those likelihoods are calculated in 0.1-arcsec offset bins instead of the previous 1-arcsec bins. Smoothing is now done onto a logarithmic profile instead of linear, to avoid over-representing likelihoods. While the likelihood lower-limit cutoff for MORX remains at 40%, past analysis has shown performance at that lower limit to be better than that; a Y2009 test of this against the predecessor QORG catalogue (Flesch & Hardcastle 2004) is given at https://quasars.org/docs/Testing-QORG-via-SDSS-DR7.txt .

5 CATALOGUE LAYOUT

The catalogue presents one line per optical object; Table 2 displays 12 sample lines which are wrapped with the left half of the block of lines shown on top of the right half. Names are given as found in the literature; else, if anonymous, the J2000 location is given as a convenience to the user. The ReadMe gives full details and indexes to the columns.

6 CONCLUSION

The MORX v2 catalogue is presented which gives 3 115 575 probable radio/X-ray associations onto optical objects, including double

[7] at https://data.sdss.org/sas/dr9/boss/sweeps/dr9/

Table 2. Sample lines from the MORX catalogue (left half placed on top of right half)

RA (J2000) IN DEGREES	DECL	NAME OR J2000 (IF NO NAME)	TYPE	R MAG	B MAG	OPT COMM	R B PSFs	Z	NAME REF	Z REF	ASSOC CONF	QSO PCT	GAL PCT	STR PCT	XRAY CONF	CHANDRA X-RAY SOURCE ID	XMM-NEWTON X-RAY SOURCE ID	SWIFT X-RAY SOURCE ID
228.7634445	61.5889250	SDSS J151503.21+613520.1	QR2	18.81	18.77	gG	- -	2.403	DR16Q	DR16Q	100	98	1	1				
228.7634696	42.0498599	NGC 5899	ARX	6.96	7.91	p+	1 1	0.008	1592	1761	100	2	92	6	99		4XMM J151503.2+420259	LSXPSJ151503.2+420259
228.7635214	36.9288189	J151503.24+365543.7	X	19.63	21.27	j+N	1 1	0.200	MQ	MQ	89	27	62	0	89	CXOG J151503.3+365543		
228.7635418	36.8302012	NPM1+37.1259	SX	8.05	8.63	b+G	- -		0982		100	1	1	98	100	CXOG J151503.2+364948	4XMM J151503.2+364948	LSXPSJ151503.2+364949
228.7636380	50.6961568	J151503.27+504146.1	R	17.52	19.61	pG	1 -	0.200	MQ	MQ	100	7	93	0				
228.7637131	22.5288475	SDSS J151503.28+223143.8	QR2	18.44	18.40	gG	- -	0.576	DR16Q	DR16Q	97	92	3	2				
228.7638054	62.3565436	J151503.31+622123.5	R	19.63	20.99	jN	1 1	0.300	MQ	MQ	100	18	82	0				
228.7638674	66.9552929	J151503.32+665719.0	R	22.32	23.43	gN	1 1		MQ		98	23	74	1				
228.7639118	36.4723147	J151503.33+362820.3	X	14.92	17.21	pmG	- -	0.500	MQ	MQ	69	19	21	29	69			
228.7639208	46.7413589	J151503.34+464428.8	R	19.70	21.02	pN	1 1	0.500	MQ	MQ	99	35	64	0				
228.7639867	38.5757067	J151503.35+383432.5	R	20.30	21.68	j+m	1 -		MQ		99	32	67	0				
228.7641297	1.5299398	SDSS J151503.38+013147.7	SR	20.86	21.08	g+G	- -		DR16Q		100	96	3	1				

ROSAT or XMM-SLEW X-RAY SOURCE ID	RADIO CONF	VLASS RADIO CORE SOURCE ID	FIRST or SUMMS RADIO CORE SOURCE ID	LoTSS RADIO CORE SOURCE ID	RACS RADIO CORE SOURCE ID	NVSS RADIO CORE SOURCE ID	DOUBLE RADIO LOBE 1 ID	DOUBLE RADIO LOBE 2 ID	LOBE MAX"
	100	VLAJ151503.04+613519.8		ILDJ151503.20+613520.3		NVSS J151503.8+613520	ILDJ151502.23+613519.5	ILDJ151504.49+613521.2	9
	100	VLAJ151503.26+420259.4	FIRSTJ151503.2+420259	ILDJ151503.24+420259.4					
1RXH J151503.5+364946									
	100			ILTJ151503.27+504146.3					
	97	VLAJ151503.38+223145.8			RACD J151503.5+223145	NVSS J151503.4+223145	FIRST J151503.4+223139	FIRST J151503.3+223149	6
	100			ILTJ151503.39+622123.7					
	98			ILDJ151503.28+665719.0					
1RXH J151503.5+362817									
	99			ILTJ151503.40+464428.3					
	99			ILTJ151503.35+383432.8					
	100	VLAJ151503.37+013147.9	FIRSTJ151503.3+013147		RACS J151503.3+013147	NVSS J151503.2+013144			

Notes on columns (see ReadMe for full descriptions):

- TYPE: R=core radio detection, X=X-ray detection, 2=double radio lobes (calculated), Q=QSO, A=AGN, G=galaxy, S=star.
- REF & ZREF: citations for name and redshift; citations are indexed in the file "MORX-references.txt".
- OPT COMM: comment on photometry: p=POSS-I magnitudes so blue is POSS-I *O*, j=POSS-II/UKST *Bj*, g=SDSS *g* & *r*, +=optically variable, m=nominal proper motion, G=*Gaia* astrometry, N=Pan-STARRS astrometry.
- R/B PSFs: '-'=stellar, 1=fuzzy, n=no PSF available, x=not seen in this band.
- ASSOC/RADIO/X-RAY CONF: calculated percentage confidence that this source is truly associated to this optical object in total/radio/X-ray, respectively.
- QSO/GAL/STR PCT: based on its photometry and the radio/X-ray association(s), the calculated percentage confidence that this optical object is a QSO/galaxy/star.
- LOBE MAX": offset of the longest radio lobe from the centroid, in arcsec. This calculation uses detection centroids, so visual lobe length can be longer.

The full table can be downloaded from http://quasars.org/morx.htm, also available in FITS.

radio lobes, using all the largest radio/X-ray source surveys to June 2023. Identifications are included to provide an informative map for pointed investigations.

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DATA AVAILABILITY

MORX v2 can be downloaded from CDS at https://cdsarc.cds.unistra.fr/viz-bin/cat/V/158 or from its home page at https://quasars.org/morx.htm which also provides a FITS file. Both sites also provide the ReadMe and the references list. Query pages are provided by CDS and NASA HEASARC at https://heasarc.gsfc.nasa.gov/W3Browse/all/morx.html.

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