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ASTRONOMY
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Galaxy coordinates

I. Accuracy of galaxy coordinates in large catalogues

G. Paturel[1] **and C. Petit**[1]

CRAL-Observatoire de Lyon, 69561 Saint-Genis Laval CEDEX, France

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Abstract. Using a generalization of the triple intercomparison method introduced by de Vaucouleurs and Head we calculated the accuracy of galaxy coordinates taken from the large catalogues. The result confirms the qualitative estimation we had in mind about the different catalogues, but for the first time it will be now possible to give a quantitative estimation of the accuracy of the position of individual galaxy, depending on the source of its coordinates. This is important in view of automatic cross-identifications which will be necessary in a near future for inclusion of very large number of new galaxies.

Key words: methods: data analysis – catalogs – galaxies: general

1. Introduction

Obviously, coordinates of astronomical objects are of great importance for identification (and even for designation). Until recent years, the accuracy of galaxy coordinates was quite poor. Most of the catalogues only gave right ascension (RA) and declination (DEC) to an accuracy of 1 arcmin (Vorontsov-Velyaminov et al. 1963–74; Zwicky et al. 1961–68; Nilson 1973). Several reasons explain this: 1) The center of a large galaxy is sometimes difficult to define accurately, especially on photographic prints because of the saturation of the nucleus. 2) The measurements were performed manually with poor star references. 3) There was no pressing need of very accurate coordinates because of the small number of catalogued galaxies. For instance, in the Reference Catalogue of Bright Galaxies (de Vaucouleurs and de Vaucouleurs, 1964) anonymous galaxies were unambiguously identified with their RA truncated to one minute (i.e. 15 arcmin).

With the development of automatic galaxy recognition, the number of new galaxies considerably grew. Into the LEDA database we catalogued 40 000 galaxies between 1983 and 1989, 73 000 in 1992, 100 000 in 1996, 160 000 in 1998 and more than one million in 2000 (Paturel et al. in preparation). Now, their number is so large that their cross-identification with previously known galaxies must be performed automatically. Since 1997 we have been engaged in this way (Paturel et al. 1996, Garnier et al. 1996; Rousseau et al. 1996; Vauglin et al. 1999). The automatic cross-identification is based on a Student's t-test criterion

$$t = \frac{1}{N}\sum_{i=1}^{N} w_i \frac{|\Delta X_i|}{\sigma(X_i)} \tag{1}$$

where w_i is the weight assigned to each parameter X_i (e.g., coordinates, magnitude, diameter, axis ratio, position angle). ΔX_i is the difference of the parameter X_i for the two galaxies in test. This method is a generalization of the ellipsoid uncertainty. This method requires that the standard deviation of each individual parameter is known. A lot of effort has been devoted to the estimation of actual uncertainty of the most common astrophysical parameters (Paturel et al. 1997) but this was not yet done for coordinates.

From the origin in 1983, we kept in the LEDA database only the best coordinates and only noted the accuracy by a flag telling that the coordinates are more accurate than 10 arcseconds. This is clearly not detailed enough for general cross-identification.

The present paper aims at improving our knowledge of coordinate accuracy for large galaxy catalogues. To this purpose, we collected original coordinates from the largest catalogues and plan to determine individual accuracy in order to calculate the actual uncertainty of coordinates of each galaxy. The method is described in Sect. 2 and the sample is presented in Sect. 3. In Sect. 4 we give the results.

2. Description of the statistical method

The method is a generalization of the method used by de Vaucouleurs & Head (1978). Let us consider a sample of objects (e.g., galaxies) with an attached parameter X (e.g., RA or DEC). We assume X is measured by two authors with two different methods giving different accuracy. The accuracy of each method will be measured by their mean errors σ_i and σ_j, assuming they are constant. These quantities are unknown. We want to determine them. If a comparison of these two sets of measurement is made using a linear regression:

$$X_i = A\,X_j \;+\; B \tag{2}$$

we obtain the standard deviation σ_{ij}. This quantity is directly measurable. We have the classical relation:

$$\sigma_{ij}^2 = \sigma_i^2 + A^2\sigma_j^2 \tag{3}$$

Send offprint requests to: G. Paturel (patu@obs.univ-lyon1.fr)

For simplicity sake, we will use variances $V = \sigma^2$. Very often, the slope A is equal to one[1]. The previous equation is then simplified in:

$$V_{ij} = V_i + V_j \tag{4}$$

In this simple comparison we have one equation with two unknowns V_i and V_j. If we have the measurements by three authors i, j, k we obtain three equations like Eq. 4 and three unknowns V_i, V_j and V_k. The system can be solved. This is the minimal case.

A generalization can be obtained when we consider N authors ($N > 3$). The number of equations is $N(N-1)/2$. This number is larger than the number N of unknowns if $N \geq 3$. The system is overdetermined. A solution can be found by a least squares method. The sum of the squares of the residual is:

$$S = \sum_{i<j} (V_{ij} - V_i - V_j)^2 \tag{5}$$

i and j varying from 1 to N. The condition

$$\partial S / \partial V_i = 0 \qquad i = 1, N \tag{6}$$

leads to the equation:

$$\sum_{i<j} (V_{ij} - V_i - V_j) = 0 \tag{7}$$

then,

$$\sum_{i<j} V_{ij} = (N-1)V_i + \sum_{i<j} V_j = 0 \qquad i = 1, N. \tag{8}$$

This can be written with matrices.

$$((A)) = ((X)).((V)) \tag{9}$$

Where the elements of the matrix $((A))$ are $\sum_{i<j} V_{ij}$, the elements of matrix $((V))$ are the unknowns $V_i,\ i = 1, N$ and where the matrix $((X))$ is:

$$((X)) = \begin{pmatrix} (N-1) & 1 & 1 & \cdots & 1 \\ 1 & (N-1) & 1 & \cdots & 1 \\ 1 & 1 & (N-1) & \cdots & 1 \\ 1 & 1 & 1 & \ddots & 1 \\ 1 & 1 & 1 & \cdots & (N-1) \end{pmatrix} \tag{10}$$

The inverse of the matrix $((X))$ is simply:

$$((X))^{-1} = T. \begin{pmatrix} 2N-3 & -1 & -1 & \cdots & -1 \\ -1 & 2N-3 & -1 & \cdots & -1 \\ -1 & -1 & 2N-3 & \cdots & -1 \\ -1 & -1 & -1 & \ddots & -1 \\ -1 & -1 & -1 & \cdots & 2N-3 \end{pmatrix} \tag{11}$$

where

$$T = \frac{1}{2(N-1)(N-2)} \tag{12}$$

Then, the solution is simply:

$$((V)) = ((X))^{-1}.((A)) \tag{13}$$

Table 1. Table of references used in the present study

code	Number	Reference	acronym
1000	11672	Nilson 1973	UGC
2000	26369	Vorontsov-V. et al. 1963–74	MCG
3000	8356	Lauberts 1982	ESO
5000	21964	Zwicky et al. 1961–68	CGCG
10000	1915	IRAS SWG 1988	IRAS
23287	91	Pantoja et al. 1997	
23290	102	Haynes et al. 1998	
24280	343	Weinberger et al. 1995	ZOA
24282	280	Stein 1996	
24351	1173	Schectman 1996	LCRS
24362	4783	Da Costa L.N., et al. 1998	SSRS2
27026	5221	Takase B. et al. 1984–1988	KUG
27048	19344	Garnier et al. 1996	
27057	2659	Karachentsev I.D. et al. 1994	FGC
27078	7489	MacGillivray et al. 1987	COSMOS
27081	7110	Loveday J. 1996	APM
27092	211	Young et al. 1998	
27094	4420	Corwin et al. 1998	
27097	5196	Klemola A.R. et al. 1994	NPM
33001	4463	Vauglin et al. 1999	DENISP

3. Construction of the sample

From the LEDA database we collected all available original equatorial coordinates RA(1950) and DEC(1950) for large catalogues together with their associated bibliographical reference. Only galaxies having two independent measurements are kept in the sample. The largest catalogues are considered first. The sample contains 48860 galaxies with 133161 coordinates measurements.

In Table 1 we give for all references included in the sample: the reference code which will be used hereafter (this code comes from LEDA database), the number of occurrences in the sample, the abbreviated reference and the acronym generally associated to this reference.

It is to be noted that some catalogues have not necessarily an overlap of their surveyed sky area with some others (e.g. ESO and CGCG/UGC). In order to avoid such cases we shared our sample in two subsamples:

a) Sample A: Northern area with references: 2000, 5000, 27048, 1000, 27078, 27026, 27097, 33001, 24362, 10000.
b) Sample B: Southern area with references: 2000, 27048, 3000, 27078, 27081, 27097, 33001, 27094, 24362, 10000. Obviously, some references cover samples A and B.

4. Mean results

We calculated the standard deviations σ_{ij} (and the corresponding variances V_{ij}) for RA and DEC from the comparison of all pairs of catalogues i and j having an intersection larger than 10 galaxies (in practice the minimum is 11). The result is presented in the Appendix. Variances V are given in $(arcmin)^2$.

For these calculations we rejected some cases where the original coordinates are clearly wrong due to a problem of iden-

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[1] This condition is very well satisfied for coordinates.

tification. Obviously, the limit of rejection depends on the quality of the coordinates. (A rejection beyond 3 arcmin would be convenient for catalogues with an accuracy of about 1 arcmin but would be clearly too large for catalogues with coordinates better than 20 arcsec). Its choice will be guided by the preliminary results (see below).

Further, when coordinates are known to have been copied from one catalogue to another (e.g., UGC and CGCG) they are rejected from the comparison.

An important remark must be made about the meaning of mean errors we are aiming at. They do not characterize only the accuracy of the method of coordinate measurement but also the mean reliability of the cross-identification of the considered catalogue.

The variances are calculated as follows:

$$V_{ij} = \frac{\sum_{i=1}^{n}(X^2) - (\sum_{i=1}^{n} X)^2/n}{n-1} \qquad (14)$$

with individual deviations $X_{ij}(RA)$ and $X_{ij}(DEC)$ in arcseconds defined as:

$$X_{ij}(RA) = 900\,(\alpha_i - \alpha_j)\cos(\frac{\delta_i+\delta_j}{2}) \qquad (15)$$

$$X_{ij}(DEC) = 60\,(\delta_i - \delta_j) \qquad (16)$$

The direct application of the method described in Sect. 2 gives individual mean errors of each catalogue. We give separately mean errors σ_α and σ_δ for RA and DEC (and corresponding variances). The combination of both mean errors in the form:

$$\sigma_{total} = \sqrt{\sigma_\alpha^2 + \sigma_\delta^2} \qquad (17)$$

represents the actual uncertainty on the position of a galaxy in a given catalogue.

It is to be noted that the application of the method may lead to negative variances ($\sigma^2 < 0$). This was already noted by de Vaucouleurs and Head. The numerical fluctuations explains this behavior when one variance is much smaller than the others. The mean error will not be calculated in such case. The individual mean errors are presented in Table 2. When the variance is negative for both RA and DEC (see for instance references 27026, 27097) we will simply not calculate the total mean error. When only one variance is negative, either in RA or in DEC (see for instance references 27078 or 33001), we assumed the same mean error on both axes by multiplying the non-zero mean error by $\sqrt{2}$ (e.g., for reference 27026 in Table 2 we adopted $\sigma_{total} = 8.8\sqrt{2} = 12.4 arcsec$).

From preliminary calculations we know that the largest mean error is about 1 arcmin. The adopted limit of rejection of discrepant measurements was then 3 arcmin (3-σ rejection).

In order to get better estimates for accurate catalogues, we applied again the method without the oldest catalogues (i.e., without references 1000, 2000, 5000 and 10000). In this case the adopted limit of rejection of discrepant measurements was reduced to 1 arcmin (roughly three times the first estimate of the largest mean errors). The results are presented in Table 3.

Table 2. Table of mean errors for sample A (Northern sample)

Ref_i	$\sigma_i(RA)$	$\sigma_i(DEC)$	σ_{total}
1000	41.8	41.0	58.6
2000	54.0	53.9	76.3
5000	39.1	37.7	54.3
10000	14.9	13.7	20.2
24362	17.5	17.2	24.5
27026	8.8	-	12.4
27048	-	-	-
27078	8.4	8.5	12.0
27097	-	-	-
33001	4.0	8.4	9.3

Table 3. Table of mean errors for sample A, restricted to the most accurate catalogues

Ref_i	$\sigma_i(RA)$	$\sigma_i(DEC)$	σ_{total}
24362	7.2	5.3	9.0
27026	6.0	2.9	6.7
27048	4.7	5.4	7.1
27078	3.1	4.1	5.2
27097	-	-	-
33001	-	1.2	1.6

Table 4. Table of mean errors for sample B

Ref_i	$\sigma_i(RA)$	$\sigma_i(DEC)$	σ_{total}
2000	55.6	54.8	78.1
3000	10.4	9.1	13.8
10000	17.7	17.3	24.8
24362	12.8	10.1	16.3
27048	7.9	7.1	10.7
27078	5.2	0.0	7.3
27081	0.0	2.8	4.0
27094	19.1	15.4	24.5
27097	0.0	0.0	0.0
33001	4.1	7.7	8.7

One reference (27097) still shows a mean error not significantly different from zero for RA. This reference is probably the most accurate. The result is confirmed with sample B in which Ref 27097 also appears.

The same procedure is applied on sample B. Similar results are presented in Tables 4 and 5.

5. Discussions

From a practical point of view we want to conclude this paper by giving a table with the best estimate of coordinates accuracy in all cases, including those where the solution cannot be found from the general method presented in Sect. 2 (i.e., 24351, 27092, 24282,23290, 24280, 23287 and 27057). For such references, the total mean error is deduced from Eq. 4 applied with only one reference (typically, the best one, assuming that the solution does not vanish). In Table 6 we give the final total mean

Table 5. Table of mean errors for sample B restricted to the most accurate catalogues

Ref_i	$\sigma_i(RA)$	$\sigma_i(DEC)$	σ_{total}
3000	5.6	3.5	6.6
24362	3.5	3.7	5.1
27048	5.9	5.8	8.3
27078	3.3	4.2	5.3
27081	2.3	2.3	3.2
27094	6.3	4.3	7.6
27097	-	-	-
33001	1.7	2.2	2.7

Table 6. Final mean errors

Ref_i	σ_{total}	reference	method
1000	58.6	Nilson 1973	General method
2000	77.2	Vorontsov-V. et al. 1963–74	General method
3000	6.6	Lauberts 1982	General method
5000	54.3	Zwicky et al. 1961–68	General method
10000	22.6	IRAS SWG 1988	General method
23287	14.3:	Pantoja et al.1997	Eq. 4 with 24280 (22)*
23290	15.7	Haynes et al. 1998	Eq. 4 with 27026 (16)
24280	14.3:	Weinberger et al. 1995	Eq. 4 with 23287 (22)*
24282	12.7	Stein 1996	Eq. 4 with 27048 (39)
24351	<2.	Schectman 1996	Eq. 4 with 27097(124)*
24362	7.3	Da Costa L.N., et al. 1998	General method
27026	6.7	Takase B. et al. 1984–1988	General method
27048	7.7	Garnier et al. 1996	General method
27057	16.4	Karachentsev I.D. et al. 1994	Eq. 4 with 27026 (98)
27078	5.3	MacGillivray et al. 1987	General method
27081	3.2	Loveday J. 1996	General method
27092	4.8	Young et al. 1998	Eq. 4 with 27097 (26)
27094	7.6	Corwin et al. 1998	General method
27097	<2.	Klemola A.R. et al. 1994	Eq. 4 with 24351(124)*
33001	2.2	Vauglin et al. 1998	General method

* Assuming the same error for both references

: Poor determination

error. When the solution comes from Eq. 4 we give the reference used as a standard and the number of comparisons which the result is based on. The result from Table 6 confirms the qualitative estimation each of us has in mind, but this table will allow us to estimate quantitatively the accuracy of individual galaxy position. This is important in view of automatic cross-identifications which will be necessary in a near future for inclusion of very large number of new galaxies.

Nevertheless, we want to recall that these mean errors reflect the astrometric precision but also the quality of the cross-identification. This is better understood when looking at result for reference 27094. This sample concerns MCG galaxies with originally poor coordinates. The new measurements have undoubtedly an intrinsic accuracy of a few arcseconds because they come from the DSS plate solution. Nevertheless, due to the badness of the original MCG coordinates (misprints, multiple objects, and poor accuracy) for this particular sample, the final mean error is about 8 arcsec.

Another phenomenon intervenes. Large galaxies have necessarily poorer coordinates because their center is somewhat difficult to define accurately. This can explain that some references (e.g., 24351 and 33001) which measure faint galaxies, have smaller standard deviations. In conclusion, there are roughly, three classes of coordinates:

- Approximate coordinates with mean error of about 1 arcmin
- Intermediate ones with an accuracy of about 15 arcsec
- Best ones based on astrometric reference frame with an accuracy of a few arcsec.

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Appendix A: table of variances and standard deviations in α and δ for references with non empty intersection

Ref_i	Ref_j	$V_{ij}(RA)$	$V_{ij}(DEC)$	n
1000	2000	1.2365	1.3123	6477
1000	5000	1.4898	1.1571	70
1000	10000	0.4708	0.5097	131
1000	23287	0.5541	0.2078	20
1000	23290	0.2302	0.3182	78
1000	24280	0.5103	0.6447	26
1000	24362	0.3877	0.5350	100
1000	27026	0.3630	0.3482	1053
1000	27048	0.3899	0.3466	5313
1000	27057	0.5327	0.5902	879
1000	27078	0.5071	0.5732	169
1000	27092	0.3183	0.1197	82
1000	27094	0.4596	0.4785	102
1000	27097	0.3404	0.2848	604
1000	33001	0.5537	0.4409	91
2000	3000	1.0384	1.0767	2437
2000	5000	1.2488	1.3099	10018
2000	10000	1.0497	1.0007	400
2000	23287	0.9242	0.7492	17
2000	23290	0.8336	0.9200	91
2000	24280	1.0914	1.3635	19
2000	24282	1.0585	0.9646	35
2000	24351	1.7715	1.0705	17
2000	24362	0.9652	0.8705	2766
2000	27026	0.7750	0.7708	1764
2000	27048	0.7535	0.7195	9505
2000	27057	0.9082	0.8086	602
2000	27078	0.8767	0.7030	2280
2000	27081	0.9346	0.9652	1055
2000	27092	0.4203	0.2742	109
2000	27094	0.9309	0.8516	3684
2000	27097	0.7066	0.7081	1886
2000	33001	0.7306	0.8275	556
3000	10000	0.1002	0.0641	272
3000	24282	0.0086	0.0044	75
3000	24351	0.0116	0.0078	30
3000	24362	0.0202	0.0118	1756
3000	27048	0.0163	0.0160	965
3000	27057	0.0285	0.0243	854
3000	27078	0.0087	0.0096	1938

Ref_i	Ref_j	$V_{ij}(RA)$	$V_{ij}(DEC)$	n
3000	27081	0.0091	0.0062	3958
3000	27094	0.1418	0.0283	35
3000	27097	0.0069	0.0029	260
3000	33001	0.0139	0.0104	969
5000	10000	0.3261	0.2685	863
5000	23287	0.5422	0.3194	24
5000	23290	0.2339	0.3059	78
5000	24282	0.2167	0.3128	11
5000	24351	0.8491	0.7503	38
5000	24362	0.3691	0.4598	237
5000	27026	0.3470	0.3276	2300
5000	27048	0.3575	0.2835	11698
5000	27057	0.4622	0.3710	489
5000	27078	0.3908	0.4280	680
5000	27092	0.3525	0.2008	121
5000	27094	0.5188	0.5345	201
5000	27097	0.3225	0.2788	3060
5000	33001	0.3974	0.4062	377
10000	23287	0.4445	0.0469	14
10000	24280	0.1409	0.0171	73
10000	24351	0.1032	0.0349	47
10000	24362	0.0922	0.0537	113
10000	27026	0.0559	0.0190	277
10000	27048	0.0642	0.0482	623
10000	27057	0.0494	0.0507	62
10000	27078	0.0892	0.0750	209
10000	27081	0.0573	0.0308	296
10000	27094	0.1606	0.2230	22
10000	27097	0.0731	0.0295	156
10000	33001	0.1275	0.1802	38
23287	24280	0.0671	0.0463	22
23290	24362	0.1012	0.1045	15
23290	27026	0.0381	0.0425	16
23290	27048	0.0897	0.1201	33
23290	27078	0.0054	0.0087	12
24282	24362	0.0026	0.0007	16
24282	27048	0.0259	0.0350	39
24282	27078	0.0114	0.0033	142
24282	27081	0.0208	0.0041	22
24282	33001	0.1033	0.0076	22
24351	24362	1.0868	0.3188	14
24351	27048	0.0255	0.0375	16
24351	27057	0.0211	0.0022	14
24351	27078	0.2147	0.6053	91
24351	27081	0.0076	0.0094	159
24351	27097	0.0004	0.0002	124
24351	33001	0.0273	0.0334	601
24362	27026	0.4443	0.2606	57
24362	27048	0.1021	0.0759	1387
24362	27057	0.3103	0.2867	64
24362	27078	0.0992	0.0792	1271
24362	27081	0.0084	0.0077	1717
24362	27094	0.1196	0.0782	335
24362	27097	0.0390	0.0583	341
24362	33001	0.0348	0.0322	433
27026	27048	0.0328	0.0257	3700
27026	27057	0.0547	0.0327	98
27026	27078	0.0064	0.0031	94
27026	27094	0.1076	0.2221	25
27026	27097	0.0028	0.0023	688
27026	33001	0.0004	0.0007	32
27048	27057	0.0510	0.0398	932
27048	27078	0.0230	0.0287	2190
27048	27081	0.0110	0.0229	425
27048	27092	0.0461	0.0237	138
27048	27094	0.2553	0.2193	167
27048	27097	0.0108	0.0092	2662
27048	33001	0.0210	0.0125	609
27057	27078	0.0213	0.0666	183
27057	27081	0.0073	0.0126	192
27057	33001	0.0128	0.0229	99
27078	27081	0.0050	0.0037	1324
27078	27094	0.0545	0.0774	480
27078	27097	0.0018	0.0186	476
27078	33001	0.0189	0.0199	1067
27081	27094	0.0629	0.0069	27
27081	27097	0.0020	0.0016	327
27081	33001	0.0103	0.0128	1419
27092	27097	0.0043	0.0025	26
27094	27097	0.0095	0.0089	54
27094	33001	0.1905	0.0721	58
27097	33001	0.0066	0.0036	259

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