Astro-photometric properties of the ICRF with respect to catalogues of quasars

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Abstract. After carrying out a cross-identification of the objects belonging both to the ICRF catalogue and to the most complete catalogue of quasars at optical wavelengths, (Véron-Cetty and Véron, 2003) we show some photometric as well as astrometric properties of the cross-identified objects (roughly 67% of the sample), comparing these properties to the general ones concerning the whole set of quasars.

1 Introduction

Since 1998, January 1st., the International Celestial Reference Frame (ICRF), consisting in a set of coordinates of extragalactic radio-sources, has been adopted by the IAU General Assembly (Kyoto, 1998) as the materialization of the International Celestial Reference System (ICRS), and must be considered by the entire astronomical community, as the conventional celestial reference frame. Despite that fact, rather few studies were devoted to the intrinsic properties of the objects of the ICRF obtained from other recent catalogues, and more specifically from catalogues of quasars obtained at optical and infrared wavelengths. This is one of the main purposes of this paper.

Moreover, in the prospect of a future densification of the ICRF, an increasing number of sources detectable from radio observations, and thus subject to possible VLBI observations, will undoubtedly be chosen as candidates to represent quasi-inertial directions in space, as it is the case at present for the 212 defining sources of the ICRF. Therefore it is interesting to evaluate the potential astrometrical improvements which should be brought by this densification, in particular concerning the sky coverage. This study is all the more interesting that in a reasonable future, with the arrival of space missions as GAIA, scheduled in the next decade, very accurate astrometric measurements of quasars and active galactic nuclei will be possible at optical wavelengths. Then the possibility of defining the new ICRF through the intermediary of the positioning of thousands of extragalactic objects, will certainly be seriously taken into account. Thus as an informative study, we consider here the total number of quasars detected today (Véron-Cetty and Véron, 2003), i.e. more than 48 000 objects, and their particularities, in the scope of such a future prospect, and in comparison with the present ICRF.

2 Generalities about quasars

Quasars are known for roughly 40 years now. The discovery of the first quasar was done in 1963, when Hazard, Mackey and Shimings, using the new technique of occultation of radiosources, got the position of the object named 3C273, with an extraordinary precision (at this epoch) of 1". Then Maarten Schmidt, working at Palomar Mount, identified 3C273 with an object of stellar aspect. The perfect correspondence between the optical and the radio positions let no doubt for the identification. The spectra obtained by M. Schmidt showed a series of emission lines, whose some were characteristics of the atom of hydrogen, all of them being

shifted toward lower wavelengths. Supposing that the other spectral lines were shifted with the same relative amount, Schmidt could identify by extrapolation well known ones, as the oxygen and the magnesium. Then he could measure the redshift $z = 0.158$.

Because of their astrometric and intrinsic physical properties, quasars must be considered as exceptional objects. Being the most powerful objects known in the universe today, their large redshifts suggest that they are very distant and that they were carried along with the expansion of the universe, even if these redshifts might arise from other phenomena as that related to the Hubble law. This is still subject to some debate. Presently most astronomers consider also that the question of what could generate such a tremendous power is solved, thus involving the presence of a supermassive black hole, located in the center of a previous galaxy, and attracting the surrounding matter. The mass of the central black hole may be a billion or more times the mass of the Sun, and the brightest quasars shine more powerfully than a thousand galaxies as ours.

With the exception of radio emission, which is often extended, the vast energy output of the quasars is concentrated into a very small area, which give them a quasi ponctual aspect, thus giving birth to their naming, "quasar" for "quasi stellar source". Fundamental characteristics can be found in their spectra, characterized by strong, broad and redshifted emission lines for wavelengths ranging in the optical and UV parts, together with a flat and often blue continuum from far infrared to X-ray.

Quasars' data are coming from a large variety of sources each of them having its own resolution and energy range. X-ray observations, characterized by a low resolution of the detectors necessitating an appropriate post-reduction with a standard software (IRAF, MIDAS), are done from satellites, as EXOSAT, ROSAT, ASCA, *Einstein*. For infra-red and optical wavelengths, spectal data, i.e. determination of the fluw w.r.t. the wavelength, can be obtained from ground-based telescopes, with radius at least 4 meters, because of the large magnitude of the quasars. Nevertheless, ground based telescopes of the order of 1 meter enable to carry out photometric data, as a magnitude in the usual UBVRIJHJK color range. The IRAS database provides far infrared data of the quasars, as a flux for each specific band filter, whereas radio telescopes enable to measure fluxes or brightness temperatures in specific frequency bands.

As soon as in 1971, i.e. less than 10 years after the discovery of the quasars, the first catalog of these exotic objects was published. It contained 202 objects (De Veny et al., 1971). Then, various observational programs lead to important increase of known quasars. All the observed ones were gathered on a regularly basis by Véron-Cetty and Véron, in ESO Scientific Reports (1984, 1985, 1987, 1989, 1991, 1993, 1996, 1998, 2000). In order to identify a quasar from any other object, Véron-Cetty and Véron (2001, 2003) have defined a quasar as a starlike object, or an object with a starlike nucleus with broad emission lines, brighter than magnitude $M_B = -23$. This last magnitude is estimated through a law involving the apparent magnitude m, the distance D, and corrective factors k and $\Delta m(z)$ (Véron-Cetty and Véron, 2001):

$$M = m + 5 - 5\log D - k + \Delta m(z) \tag{1}$$

Where the distance D is defined itself from the Hubble's law:
$D = c/H_0 \times A$

A being the photometric distance (Terrell, 1977) given by:

$$A = z\left[1 + \frac{z(1-q_0)}{\sqrt{1+2q_0z}+1+q_0z}\right] \tag{2}$$

In the equation above, k is dependent on the redshift, in the form: $k = -2.5\log(1+z)^{1-\alpha}$ and Δm is a correction to k as determined by this last equation, taking into account the spectral profile of the quasars.

In figure 1 we show the total number of quasars as recorded in the Véron-Cetty and Véron's publications, with respect to the year of publication. We can note that this number has dramatically increased in the recent years, showing an exponential type curve. This is due to the upcoming of new programs, as the 2dF (2 degrees field) QSO Redshift Survey (Crooms et al., 2000) as well as the SDSS (Sloan Digital Sky Survey) (Richards et al., 2001).

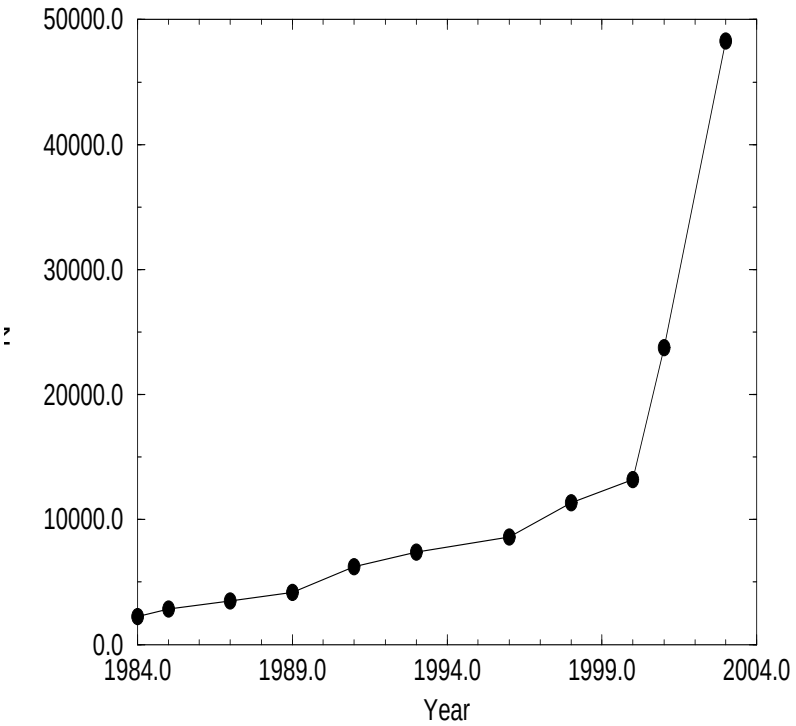

Fig. 1. Number of quasars recorded by Véron-Cetty and Véron since 1984 until 2003 in their various publications.

A first release of the 2dF QSO redshift Survey has almost doubled the number of known quasars (Véron Cetty and Véron, 2001). This release consisted in a catalog comprising more than 10 000 QSO's covering an effective area of 290 $\deg^2$. Their detection was based on single spectroscopic observations at the AAT (Anglo Australian Telescope). All the objects have their magnitude b_j included in the range $18.25 < b_j < 20.25$. In the second release, the total 2dF survey area is 740 deg^2, arranged in two $75^\circ \times 5^\circ$ declination strips centered on $\delta = -30^\circ$ and $\delta = 0^\circ$. These strips extend respectively from $\alpha = 21^h40^{mn}$ to $\alpha = 3^h15^{mn}$ and from $\alpha = 9^h50^{mn}$ to $\alpha = 14^h50^{mn}$

3 Cross-identification between ICRF and catalogues of quasars

The last version of the Véron-Cetty and Véron catalogue (Véron-Cetty and Véron, 2003), quoted as VCV2003 in the following, contains in addition to the anterior version the objects recorded in the second release of the 2dF quasar catalogue, and of the first part of the SLOAN catalogue. Therefore, it has almost doubled the number of known quasars whereas the number of active nuclei has also considerably increased: at total it contains 48 921 quasars, 876 B LAC objects, and 15 069 active galaxies, whose a majority, 11 777 ones, i.e. 78%, are Seyfert galaxies. Like the previous edition, the VCV2003 catalogue includes position at J2000.0, redshift and U,B,V photometry. When available, flux densities, expressed in Jy, at 6 cm and 11 cm are given, but in fact a very small proportion of objects have been observed at radio wavelengths: only 2850 quasars have been recorded at 6 cm (5.8 %) and only 1 418 (2.9 %) at 11 cm, nearly all of these last ones (1411 objects) have been observed in the two radio bandwidths.

Recall that the present access to the ICRS in radiowavelengths is given by the 667 extragalactic radio sources in ICRF-Ext.1 (IERS, 1999). In this extended version of the ICRF, four categories of sources are considered: defining sources, candidate sources, sources quoted as "other sources", and new sources. The first category designate 212 very stable sources whose coordinates are so stable that they have conventionally been fixed: their coordinates remain unchanged with respect to the first realization of the frame and they materialize the ICRF (Arias et al., 1995; Ma et al., 1998). The second category designates 294 sources which might be chosen as defining ones because they seem to be stable, but they need more observations to conclude about their astrometric quality. The "other" sources are useful to the densification of the frame, but do not present enough garantee of astrometric stability to be ranged in one of the two first categories. At last, a new category was added in the ICRF-Ext.1 catalogue with a set of 59 new sources which were previously not observed in the ICRF.

In table 1 we indicate the number of cross-identified objects between the ICRF and two catalogues of quasars, the PKS and the VCV2003 catalogues. We can remark that a large proportion of ICRF objects are not belonging to the VCV2003 catalogue: 38 % for the defining sources, 46 % for the candidate sources and 32 % for the other sources.

Thanks to the cross-identified objects above between the ICRF and the VCV2003 objects, it is possible, in the following, to compare the general characteristics of the ICRF (redshifts, magnitudes, flux) with respect to all the other extragalactic objects belonging to the VCV2003 catalogue.

4 Photometric properties of the ICRF quasars

In figures 2 and 3, we present respectively the histogramms of the V magnitudes of the 48921 quasars recorded in the VCV2003 catalogue, and those of the 128 cross-identified ICRF defining sources.

We can remark that a large majority of these last ones (rouhghly 75 %) are included in the range $16.5 < V < 19.5$, whereas the same percentage in the VCV2003 objects concerns the range $18.5 < V < 21.0$. From that we can assert that ICRF selected objects are globally bright objects in

Table 1. Number of quasars cross-identified between recent catalogues (Véron Cetty and Véron, 2003, PKS catalogue) and the three categories of objects used in the construction of the ICRF: defining, candidate and other sources. Three different angular thresholds have been chosen for the cross-identification: 2", 3", and 4".

Catalogue	Threshold (")	Defining ICRF	Candidate ICRF	Other ICRF
Véron Cetty	4	132/212	160/294	69 /102
and Véron, 2003		(62.2%)	(54.4%)	(67.6%)
rms(") α/δ		0.82/0.73	0.91/0.75	0.69/0.66
Véron Cetty	3	132/212	160/294	69 /102
and Véron, 2003		(62.2%)	(54.4%)	(67.6%)
rms(") α/δ		0.82/0.73	0.91/0.75	0.69/0.66
Véron Cetty	2	128/212	152/294	69 /102
and Véron, 2003		(60.3%)	(51.7%)	(67.6%)
rms(") α/δ		1.23/0.65	1.29/0.68	1.09/0.66
PKS	4	58/212	114/294	43 /102
		(27.4%)	(38.8%)	(42.1%)
rms(") α/δ		0.82/0.78	0.80/0.76	0.77/0.73
PKS	3	58/212	114/294	43 /102
		(27.4%)	(38.8%)	(42.1%)
rms(") α/δ		0.82/0.78	0.80/0.76	0.77/0.73
PKS	2	55/212	107/294	43/102
		(25.9%)	(36.4%)	(67.6%)
rms(") α/δ		0.67/0.65	0.70/0.68	0.81/0.73

optical wavelengths in comparison with the average. From the comparison between the two histogramms we can add that the proportion of the quasars among the brightest ones ($15 < V < 17$) chosen to build up the ICRF is comparatively much higher than in the VCV catalogue. Nevertheless, at the other extremity of the histogramm, the presence of very faint ICRF sources, with $V > 20$, indicates that their faintness at optical wavelengths does not seem to be a handicap for their astrometric quality, which depends essentially on the quality of their emission at radio wavelengths.

In figures 4 and 5, we show the histogramms of the same kind of study as above, but at the 6 cm wavelength. Notice that in comparison VLBI observations are generally performed at X band (3,6 cm; 8.46 Ghz) and S band (13 cm; 2.3 Ghz). Paradoxally, the feature is quite different here: whereas in the VCV2003 catalogue, the number of sources is steadily increasing for a flux at 6 cm, where a peak is observed, then slightly and gradually decreasing after, the selected cross-identified ICRF sources have been chosen in a large proportion (roughly 80 %) in the range between 0.5 Jy and 1.5 Jy.

As the redshifts of quasars is directly related to their distance by the intermediary of Hubble's law, it appears interesting to plot the V-magnitude of theses objects, which in some extent should depend also on the distance, with respect to their redshift. This is properly done in figure 6, both for the VCV2003 recorded objects (in dots) and for the ICRF quasars belonging also to this last catalogue (in large full circles).

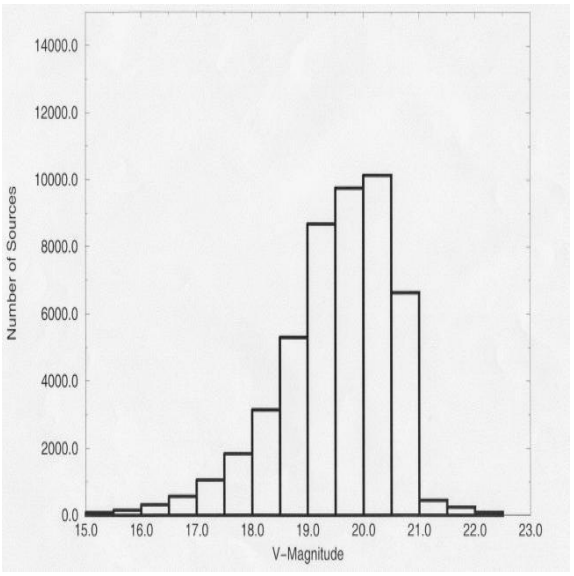

Fig. 2. Histogramm showing the number of quasars of VCV2003 catalogue with respect to their V-magnitude.

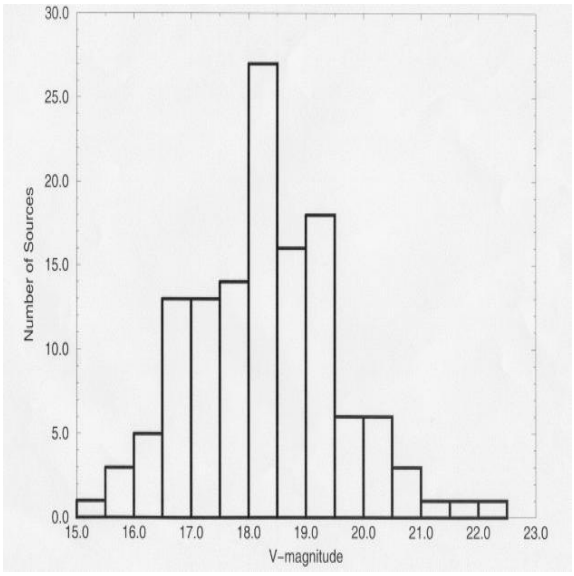

Fig. 3. Histogramm showing the number of defining sources of the ICRF cross-identified with VCV2003, with respect to their V-magnitude.

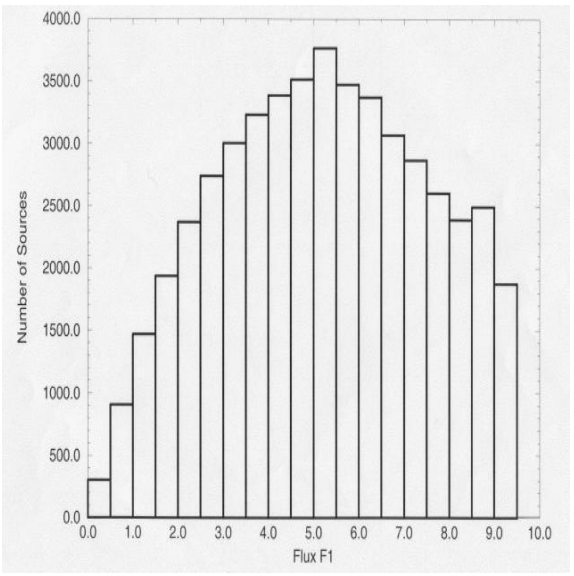

Fig. 4. Histogramm showing the number of quasars of VCV2003 catalogue with respect to their S-band flux (6 cm).

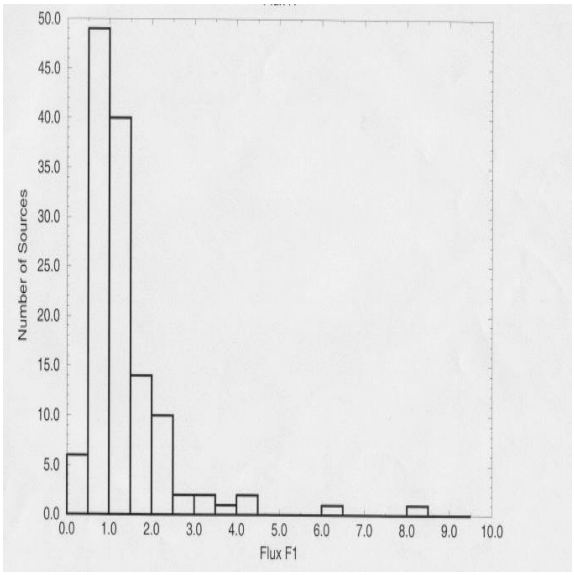

Fig. 5. Histogramm showing the number of defining sources of the ICRF cross-identified with VCV2003, with respect to their S-band flux (6 cm).

We can observe at the left part of the figure, that for a given redshift, there is well defined threshold for the upper limit in V. In opposite, this means that for a given redshift, i.e. at a given distance, it is not possible to find a quasar fainter than this magnitude threshold. As a consequence a very well defined limiting curve can thus be described, above which, no quasar can be found (in fact we can detect the presence of 3 quasars in this forbidden zone). Indeed, notice that this might be due to the definition of a quasar itself given by equations (1) and (2).

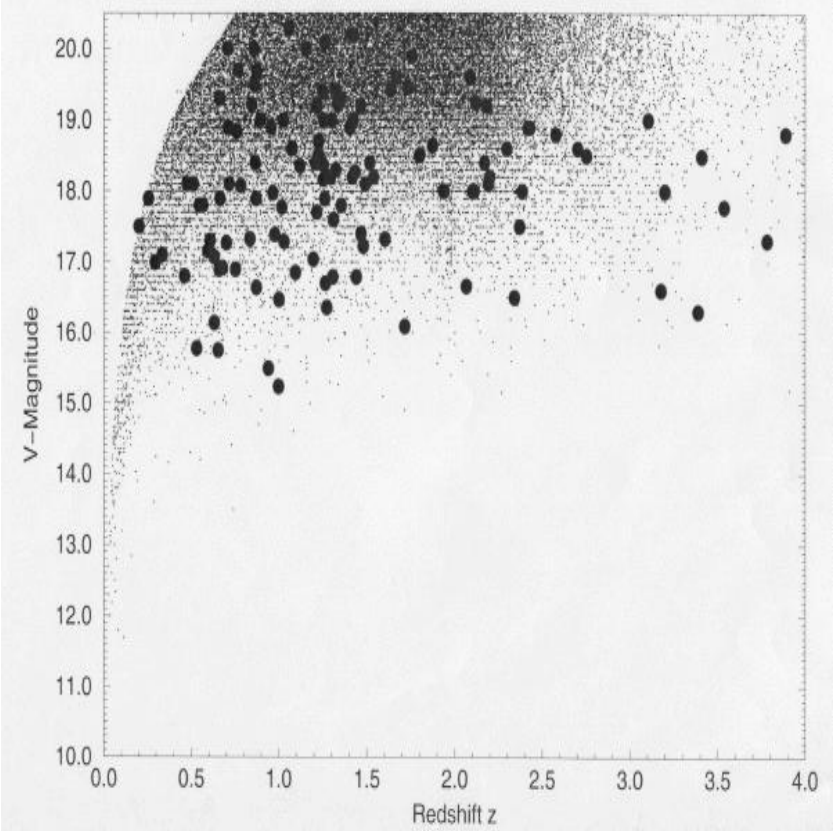

Fig. 6. Curve showing the V-magnitude of quasars of the VCV2003 catalogue (dots) and of the ICRF defining sources cross-identified with this last catalogue, with respect to their redshift.

5 About the sky coverage of the ICRS quasars and other catalogues

Although the ICRF catalogue has been adopted as the reference and conventional one since 1998, and despite its very high astrometric quality, its sky coverage is fairly poor, which is obviously due to the small number of objects: 212, if we take into account only the defining sources, 667 (for the ICRF-Ext.1) when considering also the candidate sources, the other sources, and the new sources. Indeed, the primary realization of the ICRS (International Celestial Reference System) at optical wavelengths has been carried out by the position of roughly 100 000 stars of the Hipparcos catalogue, and at a larger and less accurate extent by the 3 millions objects of the Tycho catalogue.

Here we focus our study on the intrinsic sky coverage of the ICRF and other quasar's catalogues, which will be measured in the following way: we select points of the celestial sphere separated by equal intervals, that is to say one degree in right ascension α and also in declination δ. Then for each of the points selected, we calculate the closest object of the selected catalogue we want to study. We must pay attention to the fact that the points are not regularly located on the sphere, but we choose such a repartition for reasons of commodity.

Figures 7 and 8 represent respectively in bi-dimensional coordinates (α, δ) the zones of the celestial sphere in white, for which the closest

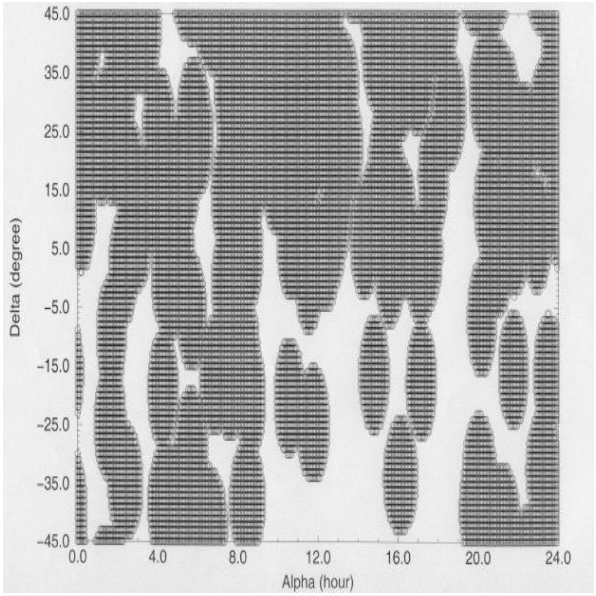

Fig. 7. Plot in black of the zones of the sky ($-45° < \delta < 45°$ for which the lowest distance to a defining source of the ICRF catalogue is less than 10°.

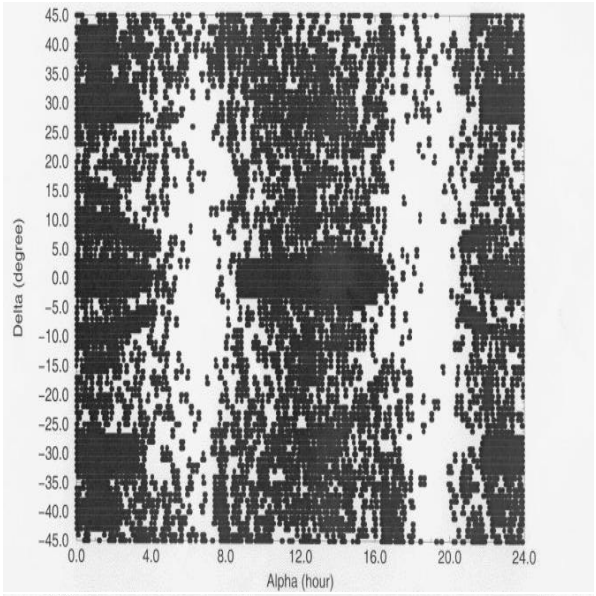

Fig. 8. Plot in black of the zones of the sky ($-45° < \delta < 45°$ for which the lowest distance to a defining source of the ICRF catalogue is less than 15°.

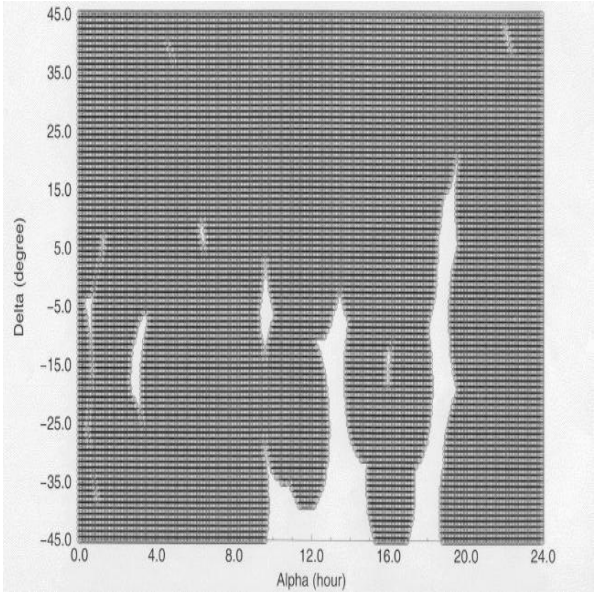

Fig. 9. Plot in black of the zones of the sky ($-45° < \delta < 45°$ for which the lowest distance to a quasar of the VCV2003 catalogue is less than 1°.

distance to an ICRF defining quasar is respectively larger then 10°, and larger than 15° (on the opposite the black zones correspond to points for which the closest defining ICRF quasar is at an angular distance respectively less than 10° and 15°). The study has been limited to zones for which $-45° < \delta < 45°$ in order to avoid distorsion at the high declinations (for which one degree separating two points in right ascension correspond to a very small angular distance). Obviously, the two figures show that the sky coverage is more deficient in the south hemisphere than in the north one, for wich the zones of depletion covers a considerably smaller surface. Moreover we have only considered here the 212 defining sources of the ICRF catalogue. The same kind of study we be done in the near future when considering the 667 extragalactic objects of the ICRF-Ext.1.

In figure 9 we present the same kind of study as above, but with the 48 291 quasars of the VCV2003 catalogue and an angular distance considerably smaller (1°). We can observe that a major part of the sky is covered by the recorded quasars at this level of angular distance, except two depletion zones covering respectively the intervals roughly from 5^h and 8^h and from 17^h to 20^h. These two zones correspond more or less to the presence of the galactic plane (the Milky Way) through which no extragalactic object can be easily observed.

6 Conclusion

In this paper we have carried out the cross-identification of the ICRF, constructed starting from observations at radio wavelengths, with VCV2003 (Véron-Cetty and Véron, 2003) which is the denser catalogue of quasars presently available, at optical wavelengths. Only a little more than 60% of the ICRF defining sources are belonging to the two catalogues. Nevertheless these common identifications enabled us to point out some general properties of the ICRF quasars, with respect to the general properties (magnitude, redshift flux at 6 cm) established statistically from the large set (48 291 objects) of the VCV2003 catalogue. In a second part we have compared the sky coverage of the ICRF catalogue and of the VCV2003. We have shown that whereas in the first case some zones of the sky are not covered at the angular distance of 15°, in the second case a large part of the sky is close to a quasar at the angular distance of 1°. No doubt that with the increasing number of quasars detected at an exponential level, it will be possible to improve drastically the astrometric measurements for the whole sky in the near future, and of course with the up-coming of the GAIA space mission which will be maybe able to detect around 500 000 quasars. This study is a first step to a more complete and detailed one, focused on the various photometric and spectral properties of the ICRF quasars but also of the BL LAC objects and Active Galaxies which belong in some significant proportion to the ICRF-Ext.1 catalogue.

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