Report of the IAU Working Group on ICRS

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Abstract. After the adoption of the ICRS and its primary materialization by the ICRF in January 1998, the last three years have witnessed a burst of interest in stellar astrometry stimulated by the availability of the ICRF and its optical counterpart. This paper reports on the activities carried out by the members of the IAU appointed working group on reference frames as well on other works directly related to the main goals of this working group.

1. Introduction

The role of high quality reference frames in astronomy has been recognized early by both theoreticians and practitioners. Astrometric data, positional or of more kinematical kind, rely on observations referred to a frame, either local or global. The choice of the reference frame may be driven by instrumental consideration or be built from deeper theoretical grounds, as is currently done with the definition of the ICRS. The main novelty in the ICRS lies in the adoption of a kinematical system which assumes that the visible universe does not rotate, that there is a particular frame where the most distant sources do not show global motion and that the remaining relative motion of the sources is negligibly small. The first constraint is not sufficient alone, because for any distribution of proper motions in a particular frame, one can always define and remove a global rotation. The absence of significant residual motion in this non-rotating frame makes the materialization of the frame permanent with no time dependent effect, unlike the former situation with the detectable motions of the stars. Imprecise knowledge of proper motions (without mentioning that of parallaxes) puts a serious limitation to the maintenance of the frame years away from the reference epoch.

As a whole these very distant extragalactic sources define and materialize a non-rotating reference system and this frame is assumed to approximate an inertial frame, defined within the context of General Relativity, through Mach's Principle. In addition to the constraint of lack of transverse motion, the relevant sources must be without structure at the mas level in the region of energy production.

The practical construction of the frame requires the consistent observations of directions of extragalactic primary sources, a set of rules to fix the pole and the origin and a process to maintain the solution in the future.

With the advent of very long baseline interferometry (VLBI), rapid improvement in positional accuracy become possible, reaching the milliarcsecond (mas) level in the 1980s and the sub-mas a few years later. This made this tech-

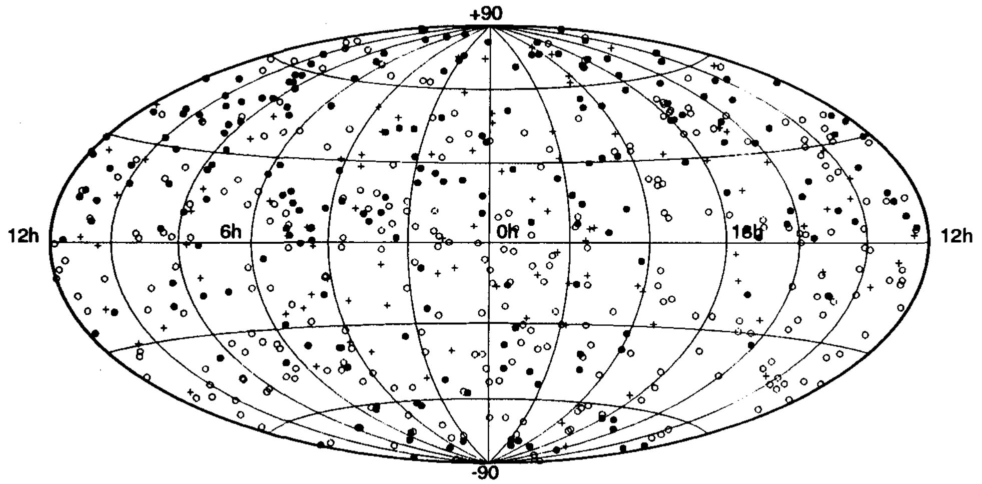

Figure 1. Space distribution of the ICRF sources in equatorial coordinates. Filled dots stand for the defining sources, open circles for the candidates sources and crosses for the other sources.

nology perfectly suitable to provide a practical realization of the kinematical reference system. The principle was adopted by the International Astronomical Union in 1991 in a series of recommendations (Bergeron, 1992) which specified the origin and the orientation of the system.

Eventually the General Assembly in Kyoto adopted the ICRF for the materialization of the International Reference System as of 1 January 1998 (Ma, 1998). The frame comprises a total of 608 radio-sources that have been carefully observed in VLBI. There are 212 defining sources with a median uncertainty in position of 0.4 mas, 294 candidate sources that could be included in the definition set in the future and 102 sources less appropriate for astrometric purposes, but useful for ties of reference frames or other purposes. The distribution of theses sources are shown in equatorial coordinates in Fig. 1. For the defining sources one should note the asymmetric distribution with 154 sources in the northern hemisphere and only 58 in the south. The catalog rests upon more than 1.6 million observations collected over fifteen years by a worldwide network. More sources will be added later, fulfilling the constraint that the directions of the defining axes are not changed in the updated frame.

On must stress that there is no best a *priori* method of observation to build the catalog and the final choice of using radio observations was dictated by the practical possibilities of the 1980s. Another choice (*e.g.* space mission) could be made in the future, should technology permit it.

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2. Organization of the Working Group

The Working Group on the International Celestial Reference System was established during the IAU General Assembly held in Kyoto in 1997 with the goal of coordinating the work of astronomers to qualify, use, extend and promote the ICRF and prepare the recommendations relevant to these topics to be submitted to the IAU General Assembly in 2000.

The Working Group comprises 36 members of which 16 are from the United States and 7 from France together with representatives from ten other countries. It is organized around six well-identified tasks (Table 1) directed by a task leader. Each member of the working group has expressed personal interest in at least one of these task. After the adoption of the ICRF and its optical counterpart in Kyoto, the work over the last three years was primarily one of consolidation and diffusion toward a wider community. A notable exception is the work within the sub-task T_5 which has far reaching consequences on conventions regarding the definition of the Celestial Pole and the rotation of the Earth.

Table 1. Tasks and task leaders of the Working Group

Task	Label of the task	Chair
T_1	Maintenance and extension of the ICRS	C. Ma
T_2	Densification at optical and IR wavelengths	S. Urban
T_3	Ties with previous and new catalogs	F. Mignard
T_4	Link to the dynamical system	M. Standish
T_5	Computational consequences	N. Capitaine
T_6	Relation with IERS	F. Arias

3. Maintenance of the ICRF

A detailed report by C. Ma on the VLBI activities related to the ICRF is included in this volume. This section will be brief, summarizing the most important points in this area. The International Earth Rotation Service has been charged by the IAU to maintain the ICRS and its materialization to tie it to other systems/frames in different wavelengths. These tasks are shared by two groups within the present structure of IERS:

- the group led by the VLBI coordinator is responsible for the VLBI analysis to provide the coordinates of radiosources for the conventional frame;
- the Celestial System Section of the Central Bureau of IERS is in charge of the maintenance of the directions of axes of the system and of the ties.

A first extension of the ICRF has been issued in 1999 under the name ICRF-ext.1. The primary objective of this first extension is to provide positions for

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extragalactic radio sources observed since July, 1995, and to refine the positions of candidate sources from additional observations. The secondary objective is to ascertain whether sources continue to be suitable for use in the ICRF. The data added to the ICRF were from December 1994 through April 1999 from both geodetic and astrometric observing programs. In total, 59 new sources not present in the ICRF were included in the solution. The same positions were kept for the defining sources (after the application of a correction of alignment of 25 μas), so that the system is unchanged in this process. The ICRF-ext.1 has been published in the IERS Annual Report for 1998 (Observatoire de Paris, 1999).

For the immediate future there are several areas of concern related to the manpower available to make observations and carry out analyses. The modeling also needs more attention, in particular the troposphere modeling, the data editing, and the weighting methods not yet used in ICRF solutions. Changes probably need to be made in analysis software to support these improvements. Perhaps older data should be discarded, but then some of the other sources with useful optical counterparts might be lost. The problem of the source structure is not a new one, but becomes more and more important as accuracy improves. But the information grows very slowly, on a source-by-source basis, and even with a major effort, the time dependance of these structural changes, makes the value of that information for the data processing questionable or at least hard to use.

The distant future with space astrometry missions under development raises the question of having the primary realization of the ICRF in other wavelengths. With SIM the number of extragalactic sources will be too small to do more than referring the global astrometry to the ICRF with a post-mission link of the same kind as with Hipparcos, however directly based on ICRF sources observed with SIM. Optical observations by FAME might be too limited toward faint sources, to supplant the ICRF, since few extragalactic sources are brighter than $V = 15$ mag in the visible. Farther in time, there is GAIA with the astrometric observations of thousands of radiosources with an accuracy better than 50 μas. This should allow us to establish a primary frame in the visible with an accuracy between 0.4 to 1 μas/yr, according to the magnitude of the source astrometric jitter. However this would not be before well into the next decade and until then, the observations in the S/X bands will prevail requiring a sustained effort of the community.

4. Densification

Since the publication of the Hipparcos and Tycho Catalogs major efforts have been undertaken to extend the coverage, in space or in magnitude range, to increase the number of reference stars with good positional and proper motion information. The ICRF is not directly usable by the majority of astronomers observing in the visible or near infra-red. The Hipparcos Catalog with about 120,000 stars continues to be the optical realization of the frame, but the densification has taken significant leaps. Hipparcos position and proper motion accuracies of the brighter stars are about 1 mas and 1 mas/yr, respectively, but the average number of stars per square degrees is just four, too small a number

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to calibrate most CCD frames. In addition, Hipparcos stars are very bright and not always usable as primary references for observations of faint sources.

4.1. Densification in the visible wavelengths

Utilizing the Tycho-1 Catalog, the ACT Reference Catalog and the Tycho Reference Catalog (TRC) increases the density of the frame ten-fold over Hipparcos, although with lower accuracy. These catalogs contain just under 1 million stars distributed across the entire sky. Position and proper motion errors of the brighter stars are quoted as about 30 mas and 2-3 mas/yr, respectively.

The Tycho-2 Catalog was released in February, 2000, and effectively replaces the ACT and TRC (Høg *et al.*, 2000). It contains 2.5 million stars throughout the sky, and is approximately 99% complete at V=11.0 and 90% at V=11.5. Positions and magnitudes are based on the same observations as the Tycho Catalog but a more advanced reduction technique yields a slight improvement in precision (25 mas for the bright stars) and a much larger size. In addition, proper motions precise to about 2.5 mas/yr are derived from a comparison with the Astrographic Catalog and 143 other ground-based catalogs, all reduced to the Hipparcos reference frame (hereafter the HCRF). The Tycho-2 Catalog supersedes in size and quality Tycho-1 itself for the astrometry and photometry of single and double stars, but it also superseded the ACT Catalog, less than three years after its release!

Table 2. Global and regional surveys in the visible and near IR

Catalog	Sources 10^6	V_{max}	σpos mas	σpos 2015 mas	σ_μ mas/yr
Hipparcos	0.1	12.4	1	20	1
ACT	1	11	30	80	3
Tycho-2	2.5	12	30	80	2
USNO A2	530	B< 20	250	400	
GSC II	500	18	250	400	20?
UCAC-1	27	16.5	20–70	50–300	2–15
SPM-2	0.3	18.5	20	50	2
2MASS	600	JHK < 14	200		
DENIS	1000 in I	I < 18	300		
	100 in J	J < 16.5			
	20 in K	K< 14			

The Southern Proper Motions (SPM) program has been released in two increments, with SPM 2.0 encompassing the first (Platais *et al.*, 1998). It contains about 320,000 stars from 5 < V < 18.5 in an irregular area of about 3700 square degrees between -22 and -43 degrees in declination, exluding fields in the Milky

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Way. Proper motion accuracies of about 2 mas/year are quoted and 20 mas in position in each coordinates. Comparisons to the Hipparcos proper motions for 10,000 stars show an offset of 0.17 and 0.43 mas/yr respectively in right ascension and declination with a standard deviation of 3.3 and 3.2 mas/yr. The proper motions are measured relative to external galaxies and the positions are on the ICRS via the Hipparcos/Tycho catalog.

As for the very large surveys, the USNO CCD Astrograph Catalog-1 (UCAC-1) has been released in early April 2000 (Zacharias *et al.*, 2000). It contains about 27 million stars south of -5 degrees declination, with an irregular northern boundary. Stars are in the magnitude range about 8 to 16, with position errors about 20 mas for 9 to 14 mag and 70 mas at 16th magnitude. Proper motion accuracies vary greatly, from 2–3 mas/yr for stars brighter than about V=12 to over 20 mas/yr, for the fainter ones, due to the lack of good positions at a first epoch. The Catalog is not complete as all problem stars (primarily multiple systems and all the bright stars) are not included. This version is the first release of an on-going program aiming at full sky coverage by 2003 after relocation of the instrument in the northern hemisphere.

The USNO A2.0 catalog contains 526 million stars from various Schmidt surveys, all measured on the PMM machine. This catalog is global, but does not contain proper motions. Error estimates are quite difficult since there is virtually nothing of comparable size and quality, but are generally expected to be in the few hundred mas range. Unlike the A1.0, the data reduction of the plates is done with the ACT catalog (Urban *et al.*, 1998) so that the positions are nominally in the ICRS.

4.2. Densification in the infra-red

In the near infra-red, two big surveys are under way and nearing completion: the 2MASS (Two Micron All Sky Survey) survey, from teams of the United-States and DENIS (Deep Near-Infrared Survey of the Southern Sky) its European counterpart limited to the southern hemisphere.

The 2MASS project is led by the University of Massachusetts with responsibility for the overall management and for developing the infrared cameras and on-site computing systems. The northern 2MASS facility began routine operations in June, 1997, and the southern facility in March, 1998. As of March, 2000, catalog quality data have been observed in an area covering 84% of the sky. Analyses of these data show that they meet and often exceed the Level 1 science requirements for the Survey.

The 2MASS project has released its second installment in 2000, containing position and brightness information for about 162 million point sources covering 40% of the sky in the wavebands J, H, K (not all sources are in the three bands). The positions of point sources are reduced with the Tycho-2 data and are therefore considered to be on the ICRS. Positional accuracy based on a comparison to the ACT are close to 100 mas in both coordinates and the internal consistency from measurement repeatability is twice smaller, with steep degradation beyond the limiting magnitude. Currently, the catalog does not contain proper motions. The magnitude cutoff of completeness depends on the galactic latitude, although it remains close to the nominal level of J=15.8, H=15.1 and Ks=14.3 mag.

DENIS is a survey led by a European consortium aiming to survey the southern sky in three wavelength bands (I, J and Ks) with limiting magnitudes 18.5, 16.5 and 14.0, respectively. Observations are performed with the 1m-ESO telescope at La Silla (Chile). The DENIS instrument is made up of a 3-channel camera built from commercially available detector arrays by the Observatoire de Paris with major contributions from other European Institutes: the IAS in Frascati, the Observatoire de Grenoble, the University of Innsbruck, the Observatoire de Lyon, and the IAC in Tenerife.

The survey is carried out by observing strips of 30 degrees in declination and 12 arcminutes in right ascension with an overlap of 2 arcminutes between consecutive strips. The observations started at the end of 1995 and will be completed by the summer of 2001 with the extraction of one billion point sources in the I band. Nearly 80% of the program has been achieved in May 2000.

The astrometry of the point sources is performed with the Tycho and Tycho-2 Catalogs and positions are nominally brought into the ICRS with an accuracy of the order of 300 mas. Although the primary purpose of the survey is for stellar physics (late type stars, low mass stars, galactic structure, star forming regions) the size of the data base combined with the care exercised in the astrometric reduction made it very relevant in the densification of the ICRF in this wavelength range. The Centre de Données Astronomiques de Strasbourg is implementing the final databases and will eventually provide access to the processed and calibrated data to the worldwide community.

The overlap between DENIS and 2MASS is large, but there is one essential difference: DENIS surveys the sky also in the I-band whereas the shortest wavelength for 2MASS is the J-band at 1.2 μm. In spite of the overlap, the two surveys are therefore complementary. For many astrophysical objects the gap between the R- and J-bands is often too large to reach solid statistical conclusions and photometry in the I-band narrows this gap significantly.

5. Observations of radio-stars

Several studies have attempted to test the Hipparcos link to the ICRF independently of the one carried out at the end of the mission. Stone (1998) has used new CCD observations of Hipparcos stars (689 in total) and that of optical counterparts of radio reference sources with well-known radio positions. Although the individual precision is not sufficient to say something about the true accuracy of the Hipparcos stars, the data are statistically able to detect a systematic difference between the ICRF and the HCRF. Indeed, the three components of the rotation at epoch 1996.5 are small and not significant at the 1σ level.

Optical positions of 327 ICRF sources have been obtained in the Hipparcos system (in two steps because the Hipparcos stars are too bright) and compared to their radio position in the ICRF (Zacharias *et al.*, 1999). In addition to random differences between the center of emission in optical and radio, there are other sources of systematic differences of kinematical origin discussed by the authors. Assuming that the final optical minus radio positions are random, the rotation angles found are again not significant at the 4-mas level. A similar effort is carried out in China by Jin W. and her collaborators with meridian circles and astrographs at the moment with an accuracy of 100 mas.

Table 3. Global orientation and spin between the FK5 and the Hipparcos Catalogs. (from Mignard and Froeschlé, 2000)

	Orientation (mas)				Spin(mas/yr)		
	J1991.25	J2000	σ			σ_{HCRF}	σ_{ICRS}
ϵ_x:	−17.3	−19.9	2.3	ω_x:	−0.30	0.10	0.27
ϵ_y:	−14.3	− 9.1	2.3	ω_y:	0.60	0.10	0.27
ϵ_z:	16.8	22.9	2.3	ω_z:	0.70	0.10	0.27

6. Comparisons to other catalogs

Soon after the publication of the Hipparcos catalog several global stellar catalogs have been evaluated with respect to the Hipparcos solution, which was virtually error free compared to these ground based observations. Such comparisons provide the overall rotation between the HCRF and the frame of the catalog, together with the regional errors.

The orientation and spin of the FK5 was obtained by Mignard & Froeschlé (1997, 2000) from a comparison of the 1233 single stars common to Hipparcos and the FK5. Results are reproduced in Table 3. The last column gives the uncertainty of the spin with respect to the ICRS from a quadratic combination of the standard error of the comparison with the residual uncertainty of the Hipparcos link to the ICRF (Kovalevsky *et al.*, 1997).

The zonal errors in the FK5 have been investigated by Zhu & Yang (1999) and Mignard & Froeschlé (2000) who confirm previous hints from Requieme (1995) of regional effects as large as 100 mas in position and 2 mas/yr in proper motion.

A similar study was carried out by the same groups for the proper motions of the PPM. At the bright end, not surprisingly, the spin of the PPM with respect to the HCRF is very similar to that of the FK5 whereas a strong magnitude equation is found when fainter stars are included in the comparison.

More recently Arias *et al.* (2000) have compared the reference frames defined by the SAO by expanding the differences with Hipparcos in a series of vector spherical harmonics. The analysis reveals large distortions ($\approx$ 1 arcsec) in the SAO, primarily in declination and a global rotation with respect to the HCRF of the order of 40 mas in each component.

7. Link to dynamical systems

The dynamical references frame is represented by the ephemerides of the planets, Moon and Sun and smaller solar system bodies. A tie between the dynamical frame and the ICRF can be realized provided planetary observations are made against sources of the ICRF or already referred to that frame in some way. This is the case for the JPL ephemerides which have been adjusted directly onto

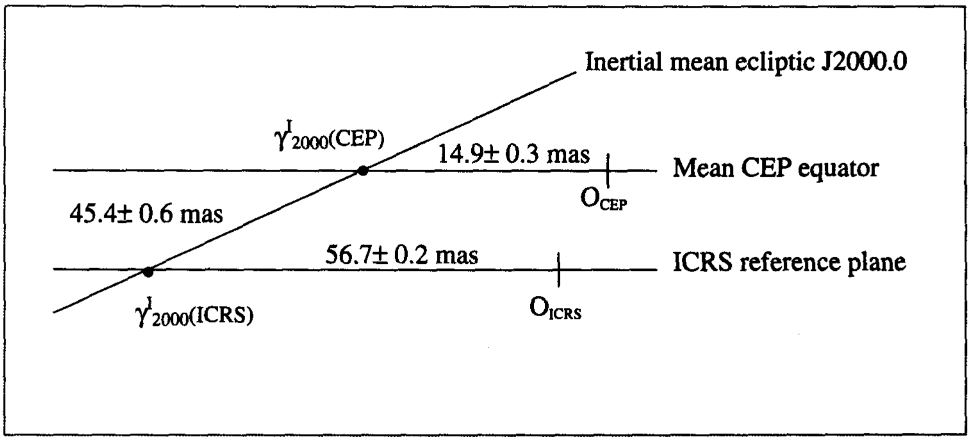

Figure 2. Relative positioning of the inertial mean ecliptic of J2000.0 with respect to the ICRS fundamental plane (from Chapront *et al.*, 1999)

the ICRF. On the other hand lunar laser ranging makes this link through the observations of the Moon and the orientation of the Earth. The JPL DE405 ephemerides of the four innermost planets, the Moon, and the Sun are all well-known with respect to each other because of the accurate ranging observations to which the ephemerides are adjusted. In turn, the orientation of this inner system onto the ICRF is determined mainly by VLBI observations of the Magellan Spacecraft orbiting Venus and also somewhat by VLBI observations of the Phobos Spacecraft approaching Mars, lunar laser ranging data, and a frame-tie linkage using VLBI, ground surveys, and LLR. The orientation is believed to be accurate at the 1-milliarcsecond level. For the outermost 5 planets, uncertainties in the orientation are overshadowed by uncertainties in the ephemerides themselves; these are about 30 mas for Jupiter and 100 mas for Saturn, Uranus, Neptune, and Pluto.

As for LLR, normal points of 25 years of ranging data have been reprocessed by J. Chapront *et al.* (1999) to determine the position of the inertial mean ecliptic of J2000.0 with respect to the ICRS. The ecliptic comes into play through the orbital and rotational motion of the Moon while the ICRS enters through the orientation of the Earth and the station coordinates given in the ITRF. An analytical solution for precession and nutation contributes to the definition of the mean celestial equator for J2000.0. The main results are shown in Fig. 2 with the position of the inertial mean ecliptic with respect to the ICRS reference plane. The obliquity (inertial ecliptic to mean equator) is found as $\epsilon = 23°26'21''.40532 \pm 0.07$ mas and $\epsilon = 23°26'21''.41096 \pm 0.06$ mas for the inertial ecliptic to ICRS reference plane.

8. Computational consequences

A tremendous activity has taken place in this area since the adoption of the ICRS and its associated frames. These studies are primarily related to the intermediate system used in the transformation from the Terrestrial Reference System to the Celestial Reference System and involve a new definition of the CEP and the adoption of an origin in the corresponding equator. The discussions and conclusions are summarized elsewhere in this volume and in a comprehensive and technical paper by Capitaine *et al.* (2000).

9. Conclusions

The deep impact of the near simultaneous release of the ICRF and the Hipparcos Catalog reveals itself in the variety of studies which rely totally, or to a large extent, on these high-quality frames. These wide ranging activities bear witness to the significance of reference frames in astronomy and call for further improvements, for example with the space missions under study.

Acknowledgments. This text relies widely on information and contributions provided by the chairs of the six subgroups listed at the beginning of this paper. They are gratefully acknowledged for their help and their efficiency over the last three years.

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