

## 3.5.4 ICRS Centre

### Introduction

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities are run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) of the IERS and the International VLBI Service for geodesy and astrometry (IVS), in coordination with the IAU Working Group on the Reference System. The present report was jointly prepared by the Paris Observatory and U.S. Naval Observatory components of the ICRS Centre.

The ICRS Centre web site (<http://hpiers.obspm.fr/icrs-pc>) provides information on the characterization and construction of the ICRF (radio source nomenclature, physical characteristics of radio sources, astrometric behaviour of a set of sources, radio source structure). This information is also available by anonymous ftp ([hpiers.obspm.fr/icrs-pc](ftp://hpiers.obspm.fr/icrs-pc)), and on request to the ICRS Centre ([icrs-pc@hpopa.obspm.fr](mailto:icrs-pc@hpopa.obspm.fr)).

### Maintenance of the ICRF

The process of maintenance of the ICRS requests revisions of the International Celestial Reference Frame whenever this is justified by an improvement in the VLBI technique and modeling, by an increase of the number of objects in the frame, or by an increase in the accuracy of radio source positions.

### ICRS representation by different sets of selected sources

The axes of the ICRS are materialized by the coordinates of 212 sources in the ICRF qualified as the “defining” objects of the frame. They have been selected by the Working Group on Reference Frames of the IAU by applying quality criteria to VLBI observations from 1975–1995 (Ma et al., 1997, 1998). A different selection of sources has been proposed by Feissel-Vernier (2003) based on an analysis of time series of radio source coordinates over the period 1989–2002. As a contribution to the maintenance of the primary reference frame, the quality of the realization of the ICRS by the two sets of selected sources has been compared (Arias and Bouquillon, 2004).

The analyses have been performed by making use of two VLBI catalogues elaborated from independent VLBI analysis: RSC (BKGI) 02 R 01 and RSC (IAA) 02 R 03 (IERS, 2003). Both catalogues have been compared to ICRF-Ext.1 by using two sets of stable sources: (a) ICRF defining sources, and (b) Feissel-Vernier (F-V) stable sources. The algorithm of comparison is the one currently used at the ICRS Product Centre, which models the transformation between two systems by a global rotation of axes and three defor-

mation parameters (IERS, 2003).

In the ICRF the sources have been classified by applying criteria based on the observational history of radio sources, the consistency of coordinates derived from different data subsets and the evidence of radio structure. F-V classification is mainly supported by the observational history of sources and the analysis of time series of radio source coordinates. 212 ICRF sources satisfied all criteria and have been classified as “defining”, that is, the best adapted to define the orientation of the axes of the system. F-V has studied the stability of radio source positions by statistical analysis of the time series of the yearly averaged coordinates (standard deviation, Allan standard deviation, normalized linear drift), and obtained a set of 199 stable sources. 75% of the sources selected by F-V are either ICRF “defining” or “candidate”, these latter considered as potential candidates to become defining sources in the future.

The two VLBI solutions used for these analyses are independent, and they yield to individual frames with a different space distribution of objects. When compared to a rigid frame, that is, to ICRF-Ext. 1, we conclude that the orientation of the axes of the ICRS is better realized by using the set of stable sources selected by F-V (2003). This result indicates that statistical tests should be considered when selecting a set of stable sources to define the orientation of axes of the ICRS. The F-V selection spans the interval 1989.5–2002.4, whereas ICRF used observations between 1975–1995. Limiting the time span for observations to the last years favours the quality of the realization of the frame (for further details, see Arias and Bouquillon, 2004).

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### **Investigation of future realizations of the ICRS**

Involvement by ICRS Centre personnel in the celestial reference frame VLBI program continued in 2003, increasing the number of observations of ICRF quasars in the southern celestial hemisphere and continuing an extensive observing program in the northern hemisphere. These observations have led to the completion of a second extension to the ICRF (Fey et al. 2004b), called ICRF-Ext.2. In this ICRF extension, VLBI data obtained between mid-1995 and the end of 2002 May were used, together with older data, to extend and revise the ICRF. Revised positions of ICRF candidate and “other” sources, based on inclusion of the additional data, were presented. ICRF-Ext. 1 added 59 new sources to the conventional frame. This second extension adds 50 more sources to the ICRF. For the first time, VLBA data has been used in the formation of the conventional extragalactic reference frame. Positions for the additional 109 new sources were also reported in the frame of the ICRF. All but four of

the new sources are located north of  $-30$  degrees declination. In the second extension, positions of the ICRF defining sources were held unchanged. A summary of current astrometric/geodetic observing programs and a short discussion on the evolution and future of the ICRF can also be found in Fey et al. (2004b). The ICRF-Ext.2 solution differs from that of ICRF and ICRF-Ext.1 in the use of the NMF mapping function (Niell, 1996) for troposphere modeling.

In the coming decades, there will be significant advances in the area of space-based optical astrometry. Proposed and scheduled missions such as the National Aeronautics and Space Administration's (NASA) Space Interferometry Mission (SIM) and the European Space Agency's Gaia mission will achieve positional accuracies well beyond that presently obtained by any ground-based radio interferometric measurements. During 2003, ICRS Centre personnel were involved in a joint US-German astrometric satellite program, called AMEX, proposed to NASA as a Small Explorer (SMEX) mission. Based primarily on the cancelled German DIVA mission, AMEX involved fabrication of the instrument in the US, fabrication of the spacecraft bus in Germany, and launch on a Russian vehicle. Unfortunately, the proposed mission was not chosen by NASA administrators to proceed into Phase A. ICRS Centre personnel continued to be involved in the SIM mission, expected to launch in 2009.

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#### **Monitor source structure to assess astrometric quality**

##### **VLBA Observations**

Observations of ICRF sources at radio frequencies of 2.3 GHz and 8.4 GHz using the Very Long Baseline Array (VLBA), together with up to 10 geodetic antennas, continued. These VLBA RDV observations constitute a joint program between the U.S. Naval Observatory (USNO), Goddard Space Flight Centre (GSFC) and the National Radio Astronomy Observatory (NRAO) for maintenance of the celestial and terrestrial reference frames. During the calendar year 2003, six VLBA RDV experiments were observed.

VLBA observations of selected ICRF sources intended to extend the ICRF to 24 GHz and 43 GHz continued in 2003. These observations are part of a joint program between the NASA, the USNO, the National Radio Astronomy Observatory (NRAO) and Bordeaux Observatory. The long term goals of this program are to 1) develop higher frequency reference frames for improved deep space navigation, 2) extend the VLBA calibrator catalog at 24/43 GHz, 3) provide the benefit of the ICRF catalog to new applications at these higher frequencies, and 4) study source structure variation at 24/43 GHz in order to improve the astrometric accuracy. During the calendar year 2003, two VLBA high frequency experiments (BR079C and BL115A) were calibrated and imaged.

### **The USNO Radio Reference Frame Image Database**

The VLBA observations taken under the above programs provide data suitable for imaging of the intrinsic structure of the extragalactic radio sources which make up the ICRF. Images are made at the USNO and are made available for use by anyone from the USNO Radio Reference Frame Image Database (RRFID). The RRFID can be accessed on the World Wide Web at <http://www.usno.navy.mil/RRFID/>. The RRFID contains 3060 VLBA images of 452 sources at radio frequencies of 2.3 GHz and 8.4 GHz. A recent addition to the RRFID are VLBA images of ICRF sources at radio frequencies of 24 GHz and 43 GHz. The RRFID contains 578 images of 230 sources at these frequencies.

### **Extending the ICRF to higher frequencies**

As a first step toward assessing the impact of intrinsic source structure at 24 GHz and 43 GHz, Gaussian component models were fitted to selected images. A core fraction, defined as the ratio of core flux density to total flux density, was also calculated (core flux density is defined as the CLEAN-ed flux density in an image contained within one synthesized beam whereas the total flux density is defined as the total CLEAN-ed flux density, i.e., the sum of all CLEAN model components).

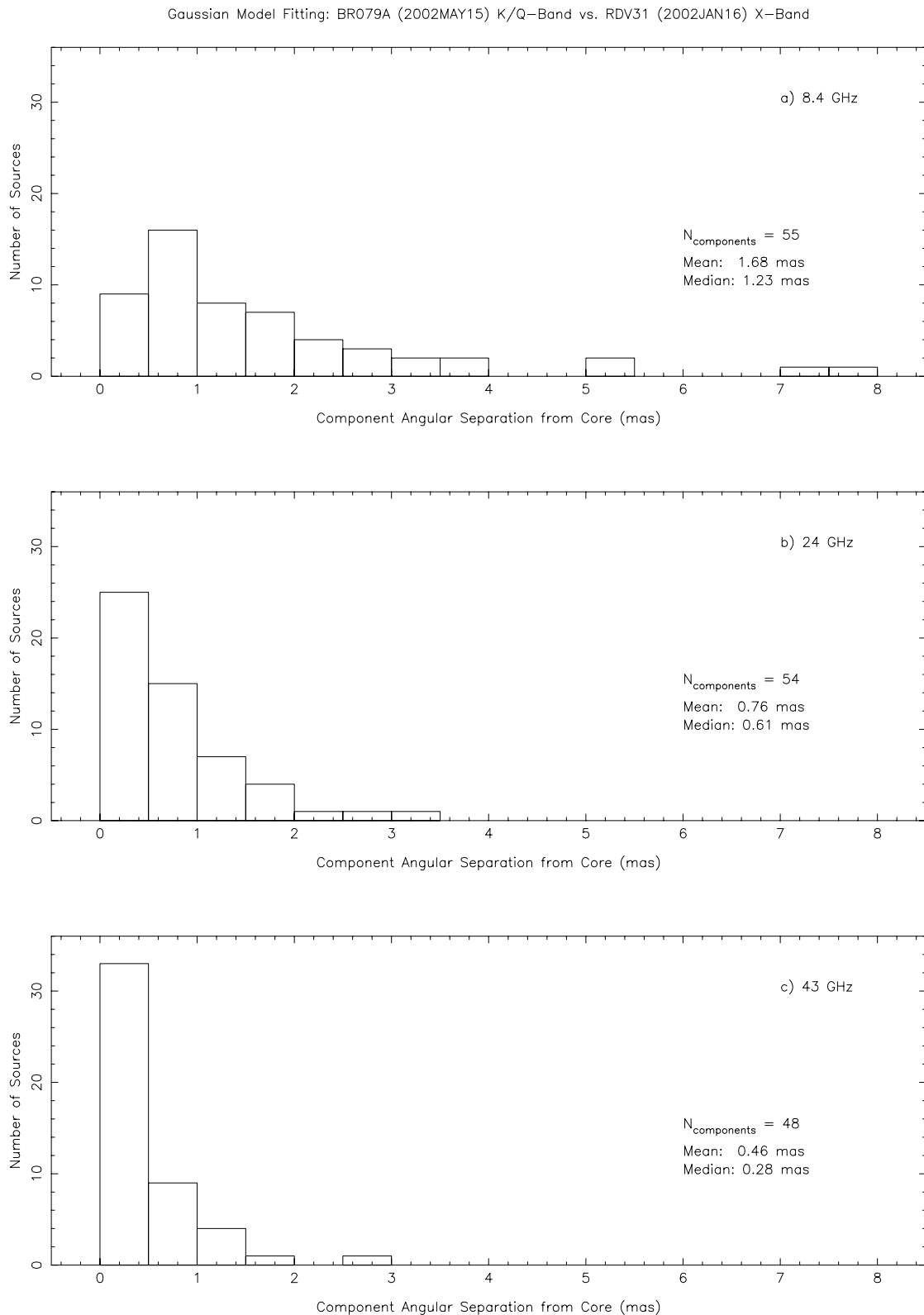
Results of the initial structure analysis are: 1) the overall spatial extent of the sources decreases as one goes to higher observing frequencies (see Figure 1); 2) source component sizes decrease as one goes from the ICRF frequency of 8.4 GHz to 24 GHz (see Figure 2); 3) source component sizes decrease only marginally as one goes from 24 GHz to 43 GHz, i.e., sources appear to be no more compact at 43 GHz than at 24 GHz (see Figure 3); and 4) there is evidence that weaker sources are more compact (but this could be a selection affect; see Figure 4). These results suggest that reference frames defined at higher radio frequencies will be less susceptible to the effects of intrinsic structure than the ICRF.

These initial results were reported at: 1) the 201st meeting of the American Astronomical Society held in Seattle, WA in 2003 January; 2) the VLBA 10th Anniversary Meeting held in Socorro, NM in 2003 June; and 3) the 3rd General Meeting of the International VLBI Service held in Ottawa, ON in 2004 February.

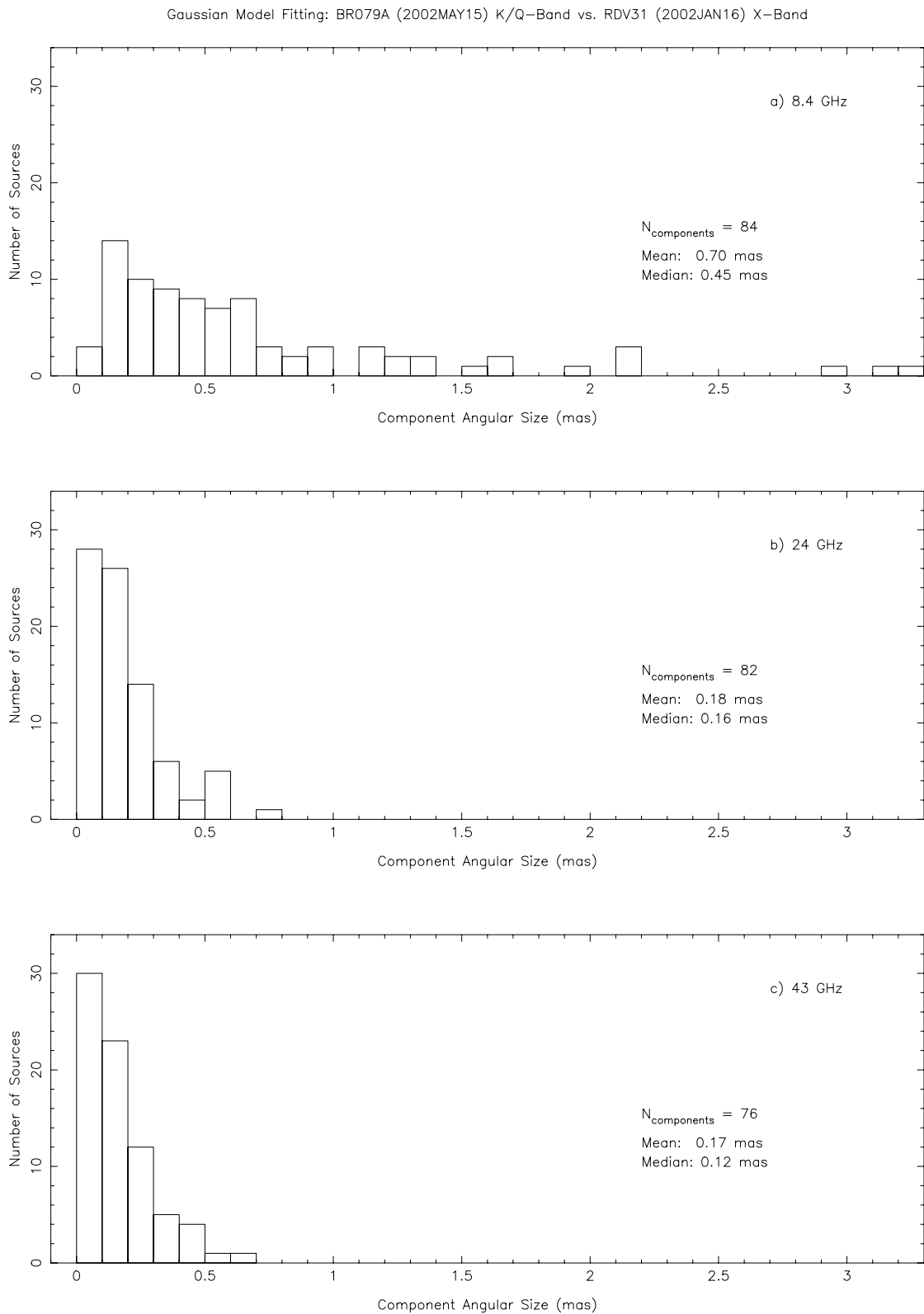
### **ICRF source component motions**

A joint program between Whitier College and the USNO to measure apparent jet velocities from the motions of source components using RRFID data at 8.4 GHz was initiated by Piner et al. (2002). To date, a total of 60 sources have been analyzed (Piner et al., 2003). Results show that the distribution of apparent component speeds peaks at low values (near  $1c$ , where  $c$  is the speed of light) but extends to values as high as  $30c$ . The average apparent speed for all components is  $4.8c$ .

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*Fig. 1: Distribution of Gaussian component angular separation from the assumed core component for the 28 common sources observed on 2002 Jan 16 and 2002 May 15 at a) 8.4 GHz, b) 24 GHz and c) 43 GHz. The core is defined as the model component fitted to the image having the smallest angular size.*



*Fig. 2: Distribution of Gaussian component angular size for the 28 common sources observed on 2002 Jan 16 and 2002 May 15 at a) 8.4 GHz, b) 24 GHz and c) 43 GHz.*

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Fig. 3: Source compactness (ratio of core flux density to total flux density) at 43 GHz versus source compactness at 24 GHz for the sources observed in the VLBA experiments BR079A, BR079B and BR049C. Core flux density is defined as the CLEAN-ed flux density in an image contained within one synthesized beam. The total flux density is defined as the total CLEAN-ed flux density (i.e., the sum of all CLEAN model components).

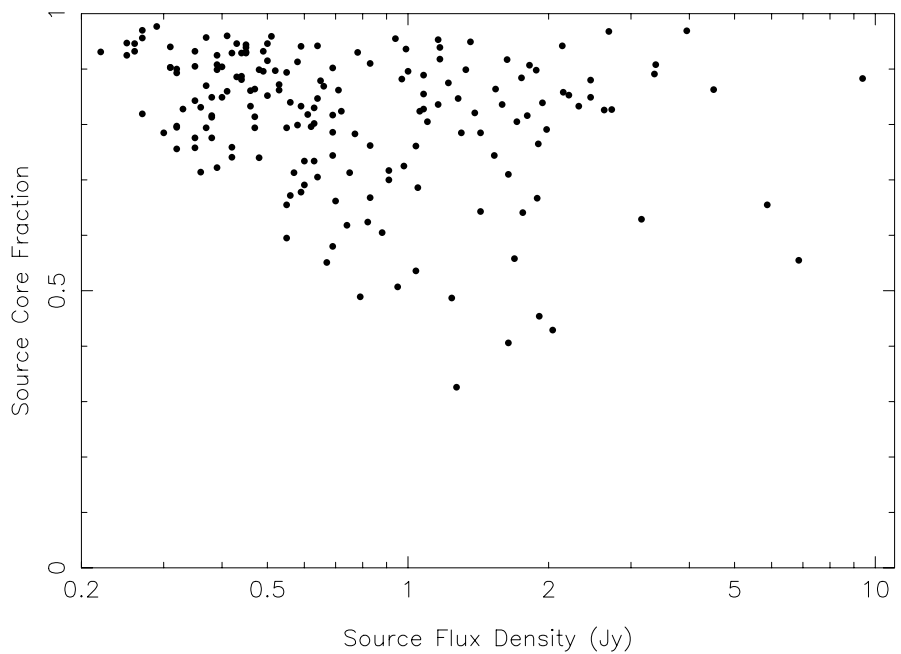
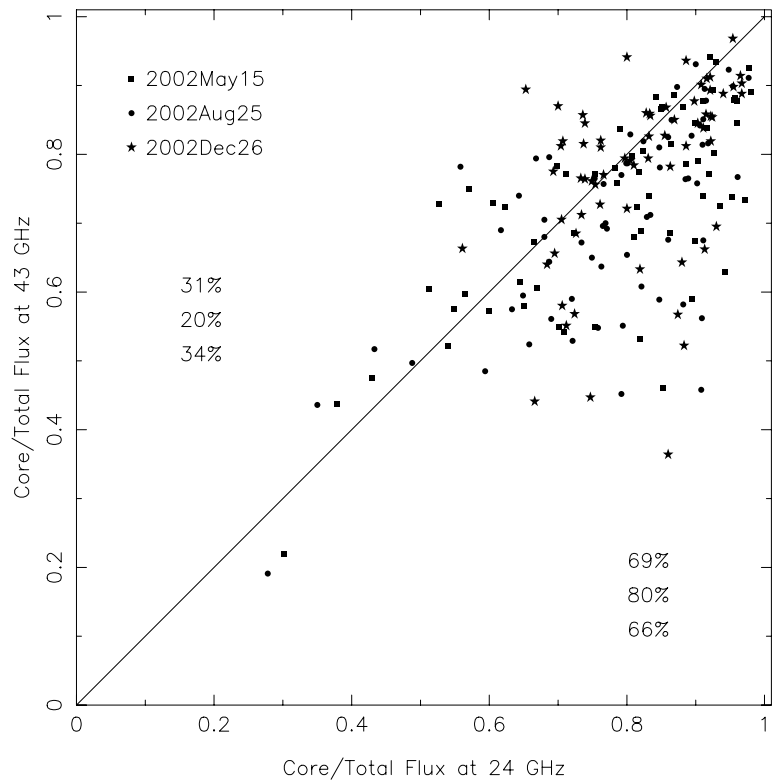


Fig. 4: The distribution of source core fraction (ratio of core flux density to total flux density) at 24 GHz versus source total flux density for the 184 ICRF source observed in VLBA experiment BL 115A. Core flux density is defined as the CLEAN-ed flux density in an image contained within one synthesized beam. The total flux density is defined as the total CLEAN-ed flux density (i.e., the sum of all CLEAN model components).

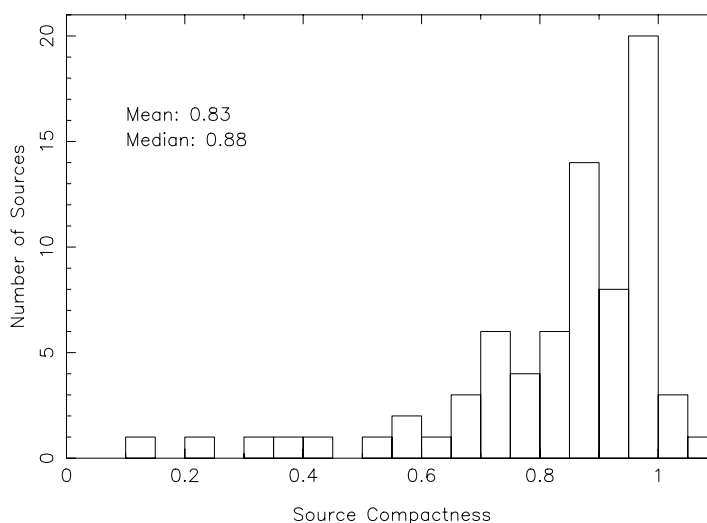
### Southern Hemisphere astrometry and imaging

The USNO and the Australia Telescope National Facility (ATNF) are collaborating in a continuing VLBI research program in Southern Hemisphere source imaging and astrometry using USNO, ATNF and ATNF-accessible facilities. These observations are aimed specifically toward improvement of the ICRF in the Southern Hemisphere. Plans include strengthening the ICRF in the Southern Hemisphere by a) increasing the reference source density with additional 2.3/8.4 GHz bandwidth-synthesis astrometric VLBI observations, and b) VLBI imaging at 8.4 GHz of ICRF sources south of  $-20$  degrees declination.

VLBI images for a total of 69 Southern Hemisphere ICRF sources were made at a frequency of 8.4 GHz using the Australian Long Baseline Array (Ojha et al., 2004). The images were used to calculate a core fraction, i.e., the ratio of core flux density to total flux density, for all observed sources. The resulting distribution shown in Fig. 5 has a mean (median) value of 0.83 (0.88) which suggests that most sources are relatively compact. However, just over half the observed sources show significant extended emission in the form of multiple compact components. These sources are probably poorly suited for high accuracy reference frame use unless intrinsic structure can be taken into account. Many of the observed sources have never been previously imaged at milliarcsecond resolution.

This program has also yielded milliarcsecond accurate radio positions for 22 Southern Hemisphere extragalactic sources not previously in the ICRF (Fey et al., 2004a). These 22 sources all have positions south of declination  $-30$  degrees (positions for ten of the sources are south of  $-60$  degrees declination). The reported positions have average formal uncertainties of 0.5 mas in right ascension and 0.6 mas in declination.

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*Fig. 5: Distribution of source compactness (ratio of core flux density to total flux density) at 8.4 GHz for 69 Southern Hemisphere ICRF sources. Core flux density is defined as the CLEAN-ed flux density in an image contained within one synthesized beam. The total flux density is defined as the total CLEAN-ed flux density (i.e., the sum of all CLEAN model components).*

### **Maintenance of the time stability of ICRF**

Feissel-Vernier (2003) explains in details the analysis of stability of a special set of radiosources selected with appropriate criteria, in order to show some possibility to improve the astrometric quality of the ICRF. This study follows an analysis of 3.4 million observations in 3338 VLBI observing sessions from 1980 up to May 2002 (Fey, 2002). These observations were leading to the source coordinates per session for 721 sources, resulting in time series of 110,111 individual positions. The results have been taken into consideration in the discussions lead by the IVS for the selection of sources in the future extensions of the ICRF.

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### **Maintenance of the link to the Hipparcos catalog**

During the report period (2003) progress has been achieved at USNO in two areas related to the maintenance of the Hipparcos link: UCAC project, and the extragalactic link.

For the densification of the optical reference frame the UCAC project (USNO CCD Astrograph Catalog) observing program is almost complete. By end of December 2003, 98% of the sky was covered. This all-sky survey will give 20 mas positions for stars in the 10 to 14 mag range, with a limiting magnitude of about  $R=16$ .

The 2nd data release (UCAC2) was presented in July 2003 at the IAU General Assembly (see Zacharias et al., 2004). This catalog contains over 48 million stars, all with proper motions, covering 87% of the sky. Proper motions were derived from AC2000, Tycho data, and re-measurements of AGK2, NPM and SPM plates. Work on a bright star supplement to UCAC2 started which will contain all Hipparcos and Tycho-2 stars not in UCAC2.

For the extragalactic link program 50 and 20 QSO source fields were observed with the KPNO 0.9m and the NOFS 1.3m telescopes, respectively. Work on the Space Interferometry Mission (SIM) preparations for the reference frame link continued, including the observing program at the 1.55m Strand Reflector at NOFS. Preliminary results were presented at the January 2004 AAS.

USNO has committed to completely measure all Hamburg Zone Astrograph and Black Birch Astrograph plates (see Figure 6). A set of 450 plates was shipped from Hamburg Bergedorf to USNO, Washington to be measured on StarScan. The remaining 3000 plates will follow soon. Most of these plates cover about 35 square degrees around extragalactic reference frame sources. There are at least 4 plates on each of over 500 fields, covering about 1/5 of the entire sky to a limiting magnitude of about 14 for epochs ranging mainly from 1977 to 1992. A mean position error of 50 mas per coordinate is expected for these about 3 million stars.

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237 ZA, 207 BB extragalactic radio source fields

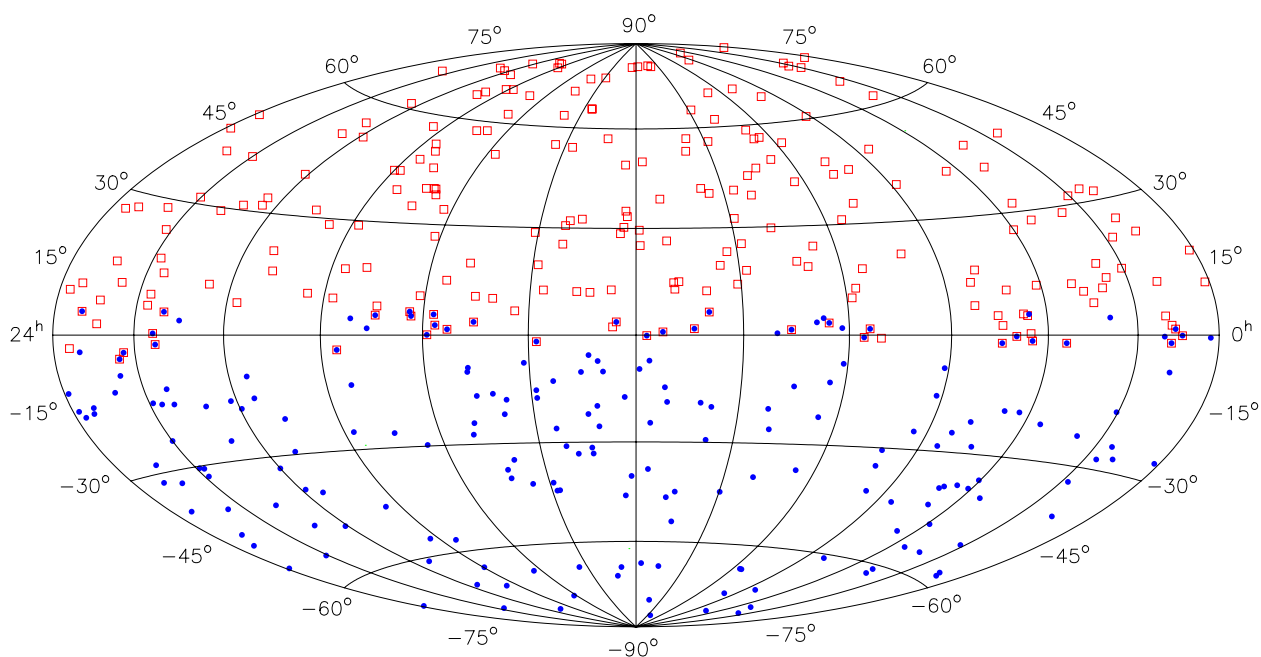


Fig. 6: Distribution of the 237 Hamburg Zone Astrograph (squares) and 207 Black Birch Astrograph (circles) plates in celestial coordinates.

### Linking the ICRF to frames at various wavelengths

The latest version of the Véron-Cetty and Véron catalogue (Véron-Cetty and Véron, 2003) contains, in addition of the precedent version the objects recorded in the second release of the 2dF quasar catalogue, and of the first part of the Sloan Digital Sky Survey catalogue. Therefore, it has almost doubled the number of known quasars whereas the number of active nuclei recorded has also considerably increased. At total 48,921 quasars are included, together with 876 BL Lac objects, and 15,069 active galaxies. Among other parameters, the catalogue includes positions at J2000.0, redshifts and U,B,V photometry. When available, flux densities, expressed in Jy., at 6 cm and 11 cm are also 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 1418 at 11 cm (2.9 %). We have performed a cross-identification of the objects in common between the ICRF and the recent catalogues of quasars. Below a threshold of 0.4", 132 sources among the 212 defining sources (62.2 %) of the ICRF have a counterpart in the Véron-Cetty and Véron catalogue, whereas the counts are respectively 160 sources among the 294 candidate sources (54.4 %) and 69 sources among the other 102 ones (67.6 %). The cross-identification enables to determine statistics concerning various photometric and physical properties of the ICRF quasars.

*Jean Souchay*

**Link to the the solar system dynamical reference through pulsar analysis**

The ephemerides of the Earth orbiting around the sun are necessary for the reduction of pulsar observations. Therefore the idea of associating pulsar timing technique with differential VLBI astrometry should provide high quality information about the position and motion of the equator, the ecliptic, the origin point of the ICRS.

Moreover, the sole analysis of signals of various pulsars should enable to construct an astrometric catalog containing the positions and the proper motions of a large number of pulsars (more than 30 observed at Nançay radiotelescope). The possibility of using high precision accumulated data coming from intensive campaigns for more than 10 years (Cognard et al., 1995) in that aim is more and more seriously investigated. In the continuity of the recent years, the observational campaign of pulsars in 2003 was very active, with a number of about 25 pulsars observed on a regularly basis. A new receiver has been implemented which provides a factor of 2.2 improvement of the signal.

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**Maintenance of the link to the solar system dynamical reference system using LLR analysis**

The position of the inertial dynamical ecliptic at a given epoch with respect to the ICRS (International Celestial Reference System) can be obtained from Lunar Laser Ranging (LLR) observations. The basic definitions concerned here are:

- the inertial dynamical ecliptic of J2000 and the ICRS reference equatorial plane;
- the inertial mean equinox of J2000  $\gamma_I^{(ICRS)}$  and the origin of right ascensions  $\alpha^{(ICRS)}$ ;
- the inclination of the inertial mean ecliptic on the ICRS equator  $\epsilon^{(ICRS)}$ .

The results given below are those mentioned in the last report. New determinations are in progress.

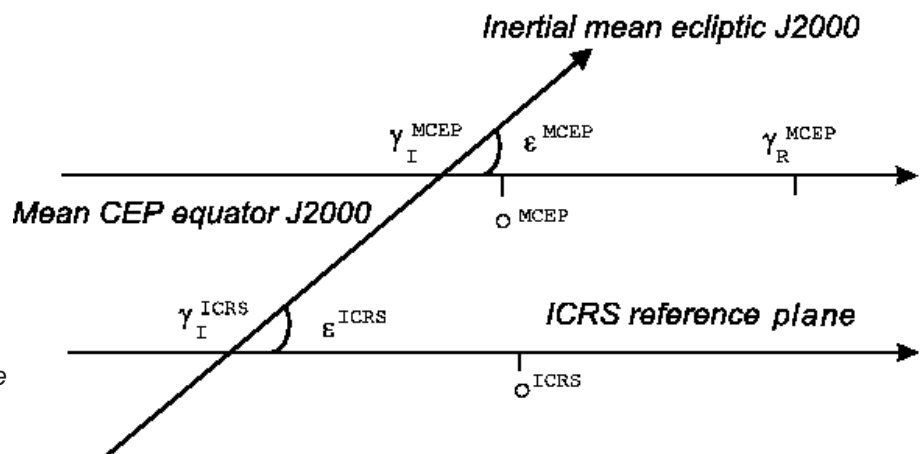


Fig. 7: Position angles of the inertial mean ecliptic of J2000.

The ICRS equator and origin of right ascensions  $o^{(\text{ICRS})}$  are involved in the transformation of the rectangular coordinates of the LLR stations in the terrestrial reference frame to the celestial J2000 equatorial coordinates. This transformation has been realized according to the lunar solution which results from weighted fits of the semi-analytical theory ELP2000-96 (orbital motion of the Moon) to the LLR observations provided between 1970 and 2002. The precession-nutation matrix PN is computed via the conventional set of values recommended by IERS (1996), in particular the nutation corrections  $\delta\varepsilon$  and  $\delta\psi$  of the series EOP(C04) produced by the Earth Orientation Centre. The position of the inertial dynamical ecliptic of J2000 with respect to the ICRS is defined by the angles:

$$\begin{aligned}\varepsilon^{(\text{ICRS})} &= 23^\circ 26' 21.411\ 00'' \pm 0.000\ 05'' \\ o^{(\text{ICRS})} \gamma_1^{(\text{ICRS})} &= -55.4 \pm 0.1 \text{ mas}\end{aligned}$$

By the same way, the position of the inertial dynamical ecliptic of J2000 can be obtained with respect to the reference frame linked to the mean Celestial Ephemeris Pole (CEP), noted here MCEP. In this case, we used another lunar solution, also issued from ELP2000-96 fitted to LLR data, where the precession-nutation is provided by analytical solutions: polynomial expressions of the precession and theory of nutation. Then, the position of the inertial dynamical ecliptic of J2000 with respect to the MCEP is defined by the angles:

$$\begin{aligned}\varepsilon^{(\text{MCEP})} &= 23^\circ 26' 21.405\ 64'' \pm 0.000\ 09'' \\ o^{(\text{MCEP})} \gamma_1^{(\text{MCEP})} &= -14.6 \pm 0.2 \text{ mas}\end{aligned}$$

From the 2 solutions linked to ICRS and MCEP, we also determine the correction  $\Delta p$  to the IAU 1976 precession constant and the value of the distance between the two inertial mean equinox of J2000  $\gamma_1^{(\text{ICRS})}$  and  $\gamma_1^{(\text{MCEP})}$ :

$$\begin{aligned}\Delta p &= -3.02 \pm 0.03 \text{ mas/a} \\ \gamma_1^{(\text{ICRS})} \gamma_1^{(\text{MCEP})} &= 44.5 \pm 0.4 \text{ mas}\end{aligned}$$

Orbital parameters of the Moon and of the Earth-Moon barycentre have also been fit, in particular the tidal component of the secular acceleration of the lunar longitude  $\Gamma$  which is related to a decrease in the Earth's rotation rate and an increase of the length of the day. The most recent determination is:

$$\Gamma = -25.858 \pm 0.003 \text{ "/cy}^2$$

Remarks:

- The uncertainties mentioned in the above evaluations represent formal uncertainties resulting from the least square fitting. Realistic uncertainties can be estimated between five and ten times these values.

- Usually  $\gamma_I^{(MCEP)}$  is named the “inertial” dynamical mean equinox of J2000. The separation from  $\gamma_I^{(MCEP)}$  to the “rotational” dynamical mean equinox of J2000  $\gamma_R^{(MCEP)}$  is 93.66 mas.

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