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 have been run jointly by the ICRS Center (US Naval Observatory and Observatoire de Paris) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU. The present report was jointly prepared by the U.S. Naval Observatory and Paris Observatory components of the ICRS Center. The ICRS Center 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 behavior of a set of sources, radio source structure). This information is also available by anonymous ftp (<hpiers.obspm.fr/iers/icrs-pc>), and on request to the ICRS Center (icrs.pc@obspm.fr).

Maintenance and extension of the ICRF

Some activities of the Paris Observatory IVS Analysis Center (OPAR, Gontier et al., 2006) are linked to the ICRS maintenance and improvement of quasar catalogues, and are also in relation to the IAU/IVS/IERS working group “Second realization of the ICRF”. We have computed the time series of radio source coordinates for approximately 500 radio sources, in parallel to the operational VLBI solutions. Most of the available diurnal VLBI sessions from 1984 involving at least three antennas are processed. The products and related statistics are made available on the OPAR Analysis Center web site <http://ivsopar.obspm.fr> in both ASCII and VOTable format. They are updated quarterly. As a contribution to the second realization of the ICRF, coordinate time series have been investigated to determine a set of sources that could be used to define the axes of the next ICRF with increased accuracy and stability. For this purpose, we developed a simple selection scheme in order to isolate 200 to 300 sources (Gontier & Lambert, 2008). We showed that using the selected sources improves the stability of the ICRF axes by about 25% with respect to the current ICRF.

On-going efforts have been made to identify the various sources of uncertainties in the nutation estimates and to minimize their effects. In this context, we have investigated the contribution of the celestial reference frame instabilities to nutation estimates (Lambert et al., 2008).

In the framework of the validation of individual VLBI references frames, individual celestial reference frames obtained in 2007 by five laboratories have been compared to ICRF-Ext.2 (Fey et al., 2004).

The reference frames analyzed

The solution RSC (AUS) 07 R 01 calculated at Geosciences Australia with the OCCAM 6.2 software is included in this report. The orientation of the celestial frame has been defined by applying a no-net-rotation constraint to the positions of 212 defining sources in ICRF-Ext.2. The a priori models are IERS 2003 for the precession, MHB2000 (Mathews et al., 2002) for the nutation. In this solution troposphere gradients have been adjusted. VLBI observations analyzed span over the period November 1979 – April 2007. Clock offsets, wet delays, gradients and EOP were considered as stochastic parameters with relevant covariance functions. VMF1 mapping function (Boehm & Schuh, 2004) has been applied for the troposphere modeling.

The individual frame RSC (BKGI) 07 R 03 elaborated at the Federal Agency for Cartography and Geodesy and the Geodetic Institute of the University of Bonn (Germany) has been evaluated using CALC 10.0 / SOLVE release 2006.12.15. The celestial reference frame has been oriented by a no-net-rotation constraint imposed to the positions of the 212 defining sources as in ICRF-Ext.1 (IERS 1999). The a priori precession and nutation models are IERS 2003. Troposphere gradients have been adjusted in the solution. The time span of the observations is January 1984 – October 2007. VMF1 mapping function has been applied for the troposphere modeling.

RSC (IAA) 07 R 02 is the extragalactic frame produced by the Institute of Applied Astronomy in Saint Petersburg, Russia with the QUASAR software. The observations range in the period August 1979 – December 2007. The celestial frame has been oriented by a no-net-rotation imposed to the positions of 212 defining sources in ICRF-Ext.2. The a priori precession and nutation models are both IAU 2000. Troposphere gradients have been adjusted in the solution.

The RSC (OPA) 07 R 04 frame was obtained at the Paris Observatory analysis center with the CALC 10.0 / Solve 2006.06.08 software. The a priori models are IERS 2003 for the precession and IAU 2000 for the nutation. A no-net-rotation constraint is applied to the 247 stable sources of Feissel-Vernier et al. (2006). The VLBI observation analyzed span over the period January 1984 – December 2007 and the NMF mapping function has been applied for the troposphere modeling. Troposphere gradients have been adjusted in the solution.

RSC (CGS) 07 R 01 is the extragalactic frame produced by the Space Geodesy Center in Matera, Italy from observations in the period August 1979 – December 2007. The software used is CALC 10.0 / SOLVE release 2006.04.05, revision 2006.04.10. The celestial frame has been oriented by a no-net-rotation imposed to the positions of 199 defining sources in ICRF-Ext.1. The a priori precession and nutation models are both IERS 1996. Troposphere gradients have been adjusted in the solution.

Positions and velocities of stations have been estimated as global parameters for the BKGI, IAA and OPA frames with a no-net-translation and a no-net-rotation constraints applied on 26 VTRF2005 stations for the BKGI, 11 VTRF2005 stations for the IAA, 35 ITRF2000 stations for the OPA and 39 ITRF2000 stations for the CGS solution. Daily station positions are estimated for the AUS frame with a no-net-translation and a no-net-rotation constraints with respect to ITRF2000 applied on a daily basis.

The characteristics of the analyzed frames are given in Table 1. Five categories of sources appear in the table: *defining*, *candidate* and *other* correspond to the classification of ICRF sources (Ma et al., 1998); *new* refers to the sources added in ICRF-Ext.2; *additional* represents sources observed in VLBI programs and not present in ICRF-Ext.2. The values of the median of the coordinate uncertainties indicate that all frames, except AUS (for sources other than *defining*), are of similar quality.

Table 1: Individual VLBI celestial reference frames analyzed. n is the number of sources, m is the median of the coordinate uncertainties. Unit: mas.

Frame	Tot.	Defining		Candidate		Other		New		Additional		dec
	N	n	m	n	m	n	m	n	m	n	m	(°)
RSC (AUS) 07 R 01	1515	210	0.05	259	0.19	4	0.32	100	0.32	942	1.68	-81;+86
RSC (BKGI) 07 R 03	1076	209	0.04	225	0.05	101	0.02	84	0.12	457	0.32	-81;+86
RSC (IAA) 07 R 02	962	212	0.06	282	0.09	102	0.03	109	0.20	257	0.47	-81;+84
RSC (OPA) 07 R 04	535	189	0.07	160	0.06	93	0.03	51	0.13	42	0.14	-81;+84
RSC (CGS) 07 R 01	637	199	0.03	213	0.03	99	0.01	67	0.06	59	0.09	-80;+84

Comparison of individual celestial frames to ICRF-Ext.2

The catalogues listed in Table 1 have been compared to ICRF-Ext.2. A revised algorithm of comparison was used. The coordinate differences between two frames are modeled by a global rotation of the axes, represented by the angles A_1, A_2, A_3, and by a deformation represented by one parameter: dz, which is a bias between the principal plane of the frame relative to that of ICRF-Ext.2. In the fitting used until 2006 slopes in right ascension and declination were modeled; as these deformation parameters proved to be negligible over some years of comparison, they have been removed from the model. Parameter dz is equivalent to the former B_δ.

$$\Delta\alpha = A_1 \text{ tg } \delta \cos \alpha + A_2 \text{ tg } \delta \sin \alpha - A_3$$

$$\Delta\delta = -A_1 \sin \alpha + A_2 \cos \alpha + dz$$

Under the hypothesis that ICRF-Ext.2 is free from deformations, the systematic effects detected in the comparisons should be interpreted as deformations in the individual frames. Defining sources common to each individual frame and ICRF-Ext.2 have been used for the comparisons. The four parameters have been evaluated by a weighted least squares fit; the equations have been weighted using the inverse of the variance of the coordinate differences. The fitted parameters allow the transformation of coordinates in the individual frames into ICRS.

Results

The results of the comparisons are shown in Table 2 for the values of the transformation parameters and in Figure 1 for the distribution of the postfit residuals.

Table 2: Transformation parameters between individual catalogues and ICRF-Ext.2. Here, N stands for the number of ICRF defining sources used for fitting the parameters. Unit: µas.

Frame	N	A_1	A_2	A_3	dz
RSC (AUS) 07 R 01	210	38 ± 58	61 ± 58	–31 ± 62	81 ± 51
RSC (BKGI) 07 R 03	209	0 ± 17	–25 ± 17	–5 ± 18	–28 ± 15
RSC (IAA) 07 R 02	212	–24 ± 19	–40 ± 19	–5 ± 10	–14 ± 17
RSC (OPA) 07 R 04	189	–35 ± 21	–11 ± 21	–14 ± 22	–15 ±18
RSC (CGS) 07 R 01	199	28 ± 22	–23 ± 21	3 ± 22	–11 ± 19

The values of the angles A_1, A_2, A_3 in Table 2 show that the individual reference frames realize the axes of the ICRF better than 40 µas, and that they are consistent at the level of their uncertainties. These uncertainties indicate that, after rotation, the inconsistency between the directions of the axes is at most 22 µas, with the exception of the AUS solution. The dz parameter quantifies the bias between the principal plane of each individual frames and that of the ICRS. For the solutions computed by AUS and BKGI, the biases are significant. In contrast, the principal planes of the OPA, CGS, and IAA frames are aligned to that of ICRS at the level of 20 µas.

Investigation of future realizations of the ICRS

Involvement by ICRS Center personnel in the celestial reference frame VLBI program continued in 2007, increasing the number of observations of ICRF quasars in the southern celestial hemisphere and continuing an extensive observing program in the northern hemisphere. This observing program will eventually result in a new realization of the ICRS, tentatively called ICRF 2. Plans for the formulation of ICRF 2 were discussed at XXVIth General Assembly of the International Astronomical Union (IAU) held in Prague, Czech Republic in August 2006. In cooperation with the International VLBI Service for Geodesy and Astrometry (IVS), a total of 17 VLBI experiments specifically dedicated to astrometric observations of

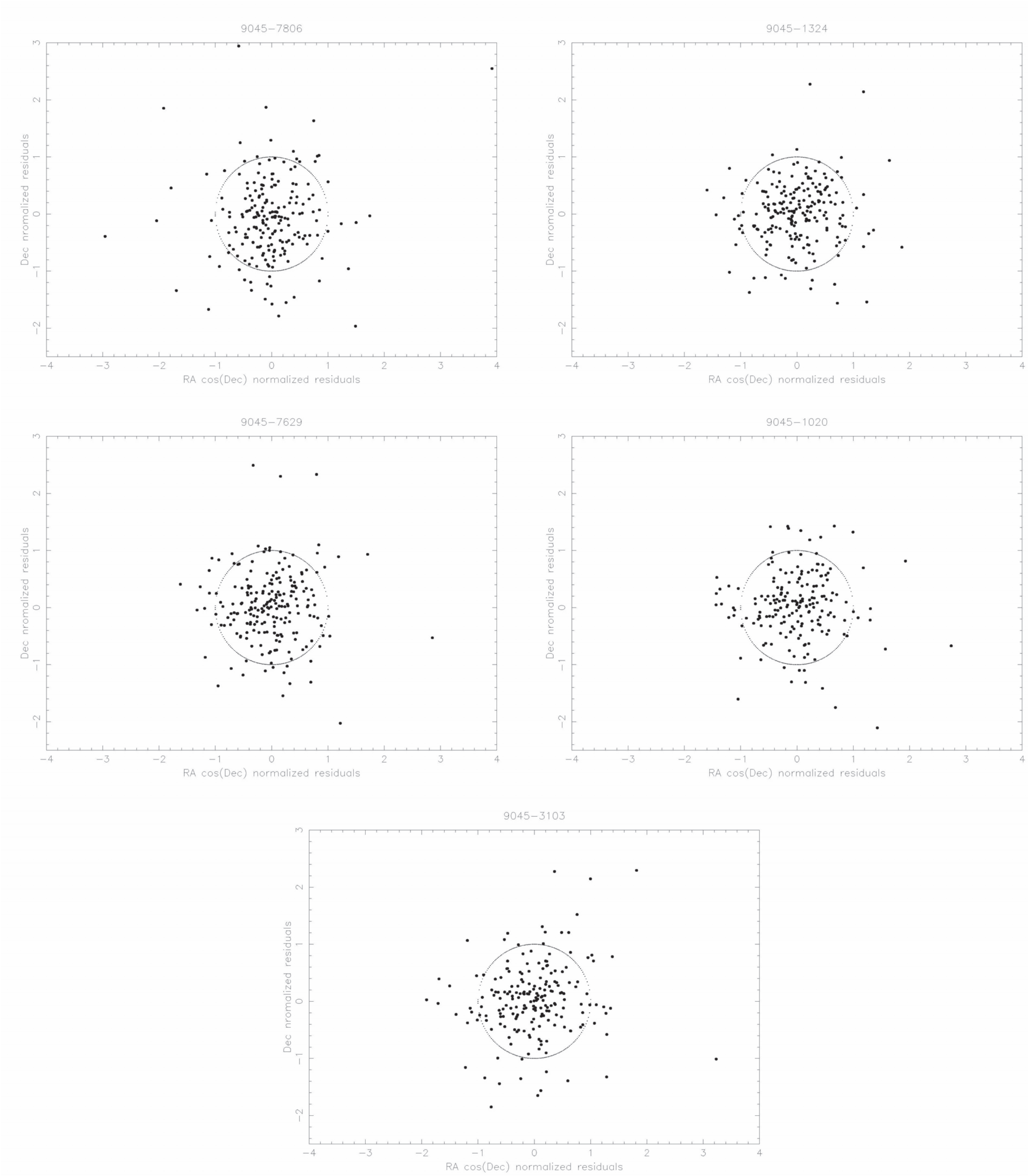

Fig. 1: Normalized residuals (ratio of the postfit residual to the uncertainty of the coordinate difference between frames). 7806: RSC (AUS) 07 R 01; 1324: RSC (BKG) 07 R 03; 7629: RSC (IAA) 07 R 02; 1020: RSC (OPA) 07 R 04; 3103: RSC (GSC) 07 R 01.

southern hemisphere celestial reference frame sources were scheduled and analyzed. The USNO and the Australia Telescope National Facility (ATNF) continue a collaborative program of VLBI research on 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. One celestial reference frame experiment, CRF-S11, was scheduled with antennas at Hobart, Australia, Hartebeesthoek, South Africa and the 70 meter Deep Space Network antenna at Tidbinbilla, Australia. In the Northern Hemisphere a major source of VLBI data continues to be the VLBA RDV series of experiments, which consist of observations of International Celestial Reference Frame (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. These VLBA RDV observations constitute a joint program between the U.S. Naval Observatory (USNO), Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO) for maintenance of the celestial and terrestrial reference frames. During calendar year 2007, six VLBA RDV experiments were observed and images from four VLBA RDV experiments were added to the USNO Radio Reference Frame Image Database (RRFID). In addition VLBA observations and analysis to extend the ICRF to K-band (24 GHz) and Q-band (43 GHz) continued in 2007. These observations are part of a joint program between the National Aeronautics and Space Administration, the USNO, the National Radio Astronomy Observatory (NRAO) and Bordeaux Observatory. Images at K-band from one experiment were added to the RRFID. Work on several refereed Journal articles presenting the results of the high frequency reference frame observations was initiated.

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-PlanetQuest) and the European Space Agency's (ESA) Gaia mission will achieve astrometric positional accuracies well beyond that presently obtained by any ground-based radio interferometric measurements. In 2007, ICRS Center personnel continued their participation in the NASA SIM mission, through direct involvement in one of the SIM key science projects: Astrophysics of Reference Frame Tie Objects. In addition, ICRS Center personnel have been working on concept development for a micro-satellite based astrometric mission, called the Joint Milli-Arcsecond Pathfinder Survey (J-MAPS), to produce milliarcsecond level astrometry for all of the bright stars up to 12th magnitude (limiting magnitude ~15–16). Together with several government and industrial partners, in 2007 ICRS Center personnel continued design and risk reductions activities for the J-MAPS program, and began planning for execution of the program funding anticipated to begin in April 2008. A symmetric optical design was completed, and adopted as the J-MAPS program baseline. Detector development progressed (Dorland et al., 2007).

Monitor source structure to assess astrometric quality

VLBA RDV Observations and Analysis

As discussed above, observations of International Celestial Reference Frame (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 in 2007. These VLBA RDV observations constitute a joint program between the U.S. Naval Observatory (USNO), Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO) for maintenance of the celestial and terrestrial reference frames. During the calendar year 2007, six VLBA RDV experiments were observed and images from four VLBA RDV experiments (RDV28, RDV61, RDV63 and RDV65) were added to the USNO Radio Reference Frame Image Database (RRFID) including images of 118 sources not previously imaged.

VLBA High Frequency Reference Frame

As also discussed above, VLBA observations to extend the ICRF to K-band (24 GHz) and Q-band (43 GHz) continued in 2007. These observations are part of a joint program between the National Aeronautics and Space Administration, the USNO, the National Radio Astronomy Observatory (NRAO) and Bordeaux Observatory. During the calendar year 2007, one VLBA high frequency experiments (BL122D) was calibrated, imaged and added to the Radio Reference Frame Image Database including images of 4 sources not previously imaged.

Several global VLBI astrometric solutions were performed using the 10 K-band VLBA experiments recorded between 2002 and 2007 in order to assess the quality of a potential high-frequency celestial reference frame. A global solution including 266 sources having three or more group delay measurements was produced. For the 191 sources with 100 or more group delays, the mean (median) formal position uncertainties were 0.07 (0.06) mas in right ascension and 0.13 (0.11) in declination. To assess the stability of the astrometric positions over time, five additional solutions were performed including the 88 sources observed in 5 or more VLBA sessions. For each solution approximately 1/5 of the sources were treated as local or “arc” parameters (i.e. a position was determined for each epoch in which the source was observed). Mean (median) weighted root-mean-square position variations were found to be 0.16 (0.13) mas in right ascension and 0.32 (0.26) mas in declination.

ICRF Maintenance in the Southern Hemisphere

In cooperation with the International VLBI Service for Geodesy and Astrometry (IVS), a total of 17 VLBI experiments specifically dedicated to astrometric observations of southern hemisphere celestial reference frame sources were scheduled and analyzed.

The USNO and the Australia Telescope National Facility (ATNF) continue a collaborative program of VLBI research on 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. One celestial reference frame experiment, CRF-S11, was scheduled with antennas at Hobart, Australia, Hartebeesthoek, South Africa and the 70-meter Deep Space Network antenna at Tidbinbilla, Australia.

A program to monitor the structure of quasars south of declination –30 degrees that are either known to be gamma-ray loud or are expected to be gamma-ray loud was initiated. The program, called TANAMI (Tracking Active galactic Nuclei with Australia Milliarcsecond Interferometry), will observe a sample of about 44 quasars at 8 GHz and 24 GHz bands, with half of the sample observed every two months. The first epoch of observations were scheduled and observed.

The Radio Reference Frame Image Database

The Radio Reference Frame Image Database (RRFID) is a web accessible database of radio frequency images of ICRF sources. The RRFID currently contains 4980 Very Long Baseline Array (VLBA) images (a 20% increase over the previous year) of 636 sources (a 23% increase over the previous year) at radio frequencies of 2.3 GHz and 8.4 GHz. Additionally, the RRFID contains 1339 images (a 16% increase over the previous year) of 270 sources (a 1% increase over the previous year) at frequencies of 24~GHz and 43~GHz. The RRFID can be accessed from the Analysis Center web page or directly at <http://rorf.usno.navy.mil/rrfid.shtml>.

Maintenance of the link to the Hipparcos catalog

During the reporting period (2007) progress has been achieved at USNO in several areas related to the maintenance of the Hipparcos link: UCAC project (work toward the final release), the extragalactic link to radio frame sources, URAT and J-MAPS.

Software development for the pixel re-reduction of the USNO CCD Astrograph Catalog (UCAC) project was completed and 4 image profile fit models will be used for final reductions. The goal is to improve completeness, astrometric and photometric accuracy significantly over the UCAC2 release. A status report on UCAC and URAT was given at the IAU Symposium 248 in Shanghai (Zacharias, 2008).

As part of the UCAC project early epoch photographic plates were measured on the StarScan machine at USNO. Astrometric reductions were completed of about 5000 plates from the AGK2, Hamburg Zone Astrograph and USNO Twin Astrograph (Black Birch, New Zealand) programs (Zacharias et al., 2008).

The Southern Proper Motion (SPM) pixel data from Precision Measure Machine (PMM) scans of all applicable plates (Yale, San Juan program) were obtained from the Naval Observatory Flagstaff Station (NOFS) and processed through a modified StarScan pipe-

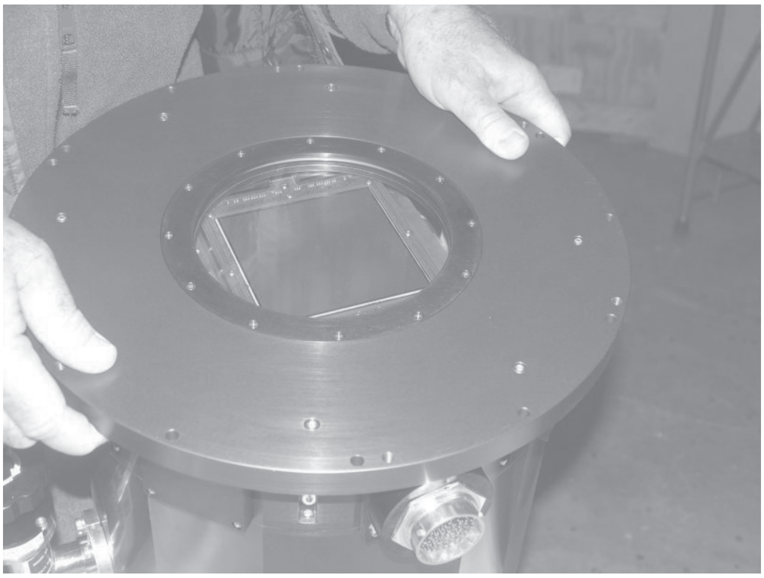

Fig. 3: 10k CCD chip inside dewar for URAT project test observations.

blooming scheme to obtain accurate positions of bright stars (Zacharias et al., 2007). Phase 1 of the URAT project will have 4 of these detectors mounted at a new focal plane assembly at the USNO "redlens" astrograph. The goal is to produce an all-sky astrometric catalog more accurate than UCAC and 2 magnitudes deeper, including proper motions and parallaxes on the HCRF utilizing Tycho-2 as reference stars. For an update on the URAT project see (Zacharias, 2008).

Maintenance of the link to the solar system dynamical reference frame using Lunar Laser Ranging analyses

Lunar laser observations (LLR normal points) consist in measurements of the round-trip travel time of the light between a terrestrial station and a lunar reflector. Several analyses on the LLR data have been performed by the lunar analysis center POLAC (Paris Observatory Lunar Analyses Center) located at SYRTE laboratory (Observatoire de Paris, France). Some of them concern in particular the orientation of the solar system dynamical reference frame with respect to other reference frames.

The solar system dynamical reference frame is materialized by the dynamical mean ecliptic and equinox (epoch J2000.0) related to the orbit of the Moon through the ephemerides of the semi-analytical lunar solution ELP (Chapront-Touzé M. and Chapront J., 1997). The analysis of the LLR observations enables to define the orientation of dynamical mean ecliptic and equinox of J2000 with respect to ICRS. In the same time, the LLR analysis enables to determine other parameters and to update the ELP theory (Chapront J. et al., 2002, 2003; Chapront J. and Francou G., 2006).

The position of the dynamical mean ecliptic with respect to the ICRS is defined by two angles: $\varepsilon^{(ICRS)}$, the inclination of the dynamical mean ecliptic to the equator of ICRS, and $\varphi^{(ICRS)}$, the angle between the origin $o^{(ICRS)}$ of right ascensions on the equator of ICRS and the ascending node $\gamma_I^{(ICRS)}$ of the dynamical mean ecliptic on the equator of ICRS.

Between 1969 and 2006, over 17000 LLR normal points have been provided by three stations: McDonald (Fort Davis, Texas), Observatoire de la Côte d'Azur (Grasse, France), Haleakala (Maui, Hawaii). In 2007, only McDonald observatory was operational (76 normal points). Comparing our analyses 2008 with those made the last year, there is no change in the post-fit residuals between observed and computed values of the distance station-reflector. There is also no change in the evaluation of these two angles $\varepsilon^{(ICRS)}$ and $\varphi^{(ICRS)}$:

$$\varepsilon^{(ICRS)} = 23°26'21.411'' \pm 0.001''$$

$$\varphi^{(ICRS)} = o^{(ICRS)}\gamma_I^{(ICRS)} = -0.055'' \pm 0.001''$$

Optical-Radio Offsets at the Milli-arcsecond level

The quasars that form the ICRF are in general radio-compact at the level of a few mas. This would imply radio emission from the base of the radio jet, much close to the accretion disk from where the bulk of the optical emission is expected. As a result the optical to radio centroid offset for the ICRF sources should lie in the sub-mas region. Yet, since earliest astrographic plate observations (Costa & Loyola, 1998) and earliest attempts to global analysis (Silva Neto et al., 2002), up to recent CCD infrared observations (Camargo et al., 2005), some conspicuously large optical-radio offsets are found. Though a large proportion of the offsets found in the earliest works would rather represent bias in the optical stellar catalogues used therein, a statistical proportion remained unexplained. Recent observational efforts focus on the astrometric determination of the optical-radio offset for particular sources, where it may be found at the level of few tens of mas, attainable by carefully planned optical measurements. The Observatorio do Valongo/UFRJ and the Observatorio Nacional/MCT joint teams (J.I.B. Camargo and co-proposers) have been conducting astrometric observations at the SOAR telescope, 4.1m, SOI CCD camera, in the R filter, for a group of selected ICRF quasars. The SNR compound trough multiple short integrations reaches 100, to derive the objects astrometry at the 10 mas level, referred to local stellar catalogues based on the UCAC2 frame.

The ICRS Center is concerned by the continuation of this program with the same team (A.H. Andrei and co-proposers), at the ESO 2.2m telescope, using the WFI CDD camera, and R filter. Similar astrometric precision is derived. In this case the large WFI enables to directly use UCAC2 reference stars by a global reduction strategy. The same Rio de Janeiro and Paris consortium also develops a second strategy, at the same telescope and CCD camera, using R and B filters, and longer exposures that are combined to reach SNR of 1000. In this experiment pairs of quasars for which there are precise VLBI positions have their relative astrometry determined. In this way no external optical catalogue is needed but for a general orientation of the field and to calculate the pixel scale. The relative optical positions can thus be derived to the precision of a few mas and compared to the relative radio position.

These programs aim to contribute to the extension of the ICRF to the optical domain. They can also contribute to the fundamental quasar catalogues of the forthcoming SIM and GAIA missions, as well as to the tying of such frames to the ICRF itself.

First attempts of link between dynamical planetary reference frame and ICRF via VLBI observations of millisecond pulsars

An independent way to establish a link between a dynamical reference frame built on the basis of a planetary ephemeris and the ICRF, is to use VLBI observations of millisecond pulsars combined with pulsar timing.

Coordinates that are determined by using pulsar timing data are expressed in the reference frame of the planetary ephemerides used in the reduction process of the timing observations. We note (α_{TOA}, δ_{TOA}) the pulsar coordinates obtained with pulsar timing. In the other hand, VLBI observations of the same pulsars done by using ICRF sources as calibration are given directly in ICRF. Let us note (α_{VLBI}, δ_{VLBI}) the coordinates of the pulsars obtained with VLBI. The comparisons between these two sets of coordinates (α_{TOA}, δ_{TOA}) and (α_{VLBI}, δ_{VLBI}) give then the rotations between the ICRF and the dynamical reference frame of the planetary reference frame as well as possible secular drift of the dynamical reference frame if the comparisons are extended in time.

As the two methods of observations (pulsar timing and VLBI observations) are both at the mas level accuracy in the position determinations, one can estimate that such algorithm can insure a mas accuracy in the link between ICRF and the dynamical reference frame. Furthermore, as neither the pulsar timing nor the VLBI pulsar observations are included in the fit of the planetary ephemerides to observations, the algorithm of link proposed above enables also a check of the capabilities of extrapolation of the planetary ephemerides.

In 2007–2008, observations of millisecond pulsars are proposed at the European VLBI Network (EVN). Several parameters were used to make a first selection of candidates.

- The pulsar must emit strongly enough to be detectable with VLBI antennas. Usually, the minimal emitted flux of a source observed at 1.4 Ghz is about 5 mJy. This is the limit used in this selection.
- The pulsar has to have a regular timing follow-up in the northern hemisphere (Nançay Radio Telescope).
- As the goal of the VLBI observations of the pulsar is to obtain coordinates expressed directly in ICRF, ICRF sources have to

be in the vicinity of the pulsar. Usually, during VLBI acquisition, the calibration sources have to be less than 5 degrees away from the observed source.

Based on a list of 97 pulsars identified from the NRAO VLA sky survey (NVSS) at 1.4 Ghz (Han & Tian, 1999), we have selected pulsars which emit more than 5 mJy as observed by the NVSS at 1.4 Ghz, and which are also observed by the NRT for timing observations. Moreover they must have in their vicinity (less than 5 degrees away) at least one ICRF-Ext.2 source. With such criteria, we have obtained 18 possible candidates. 10 of them were already observed by the NVSS in a goal of polarization measurements but not for astrometric calibration and 8 other ones were not observed by the NVSS due to scintillations.

Furthermore, for reasons of visibility and to optimize the (U, V) coverage, we limit the candidates to have positive declination in keeping in mind that to optimize the (U, V) coverage, declination must be greater then 20 degrees. 11 pulsars remain with 3 of them having declinations about 10 degrees.

One can find in Table 3 the list of the candidate pulsars (PSR) as well as the ICRF reference sources (J). For PSR, the first column is the official J2000 denomination, the two following columns are the J2000 right ascensions in hours and declinations in degrees. The

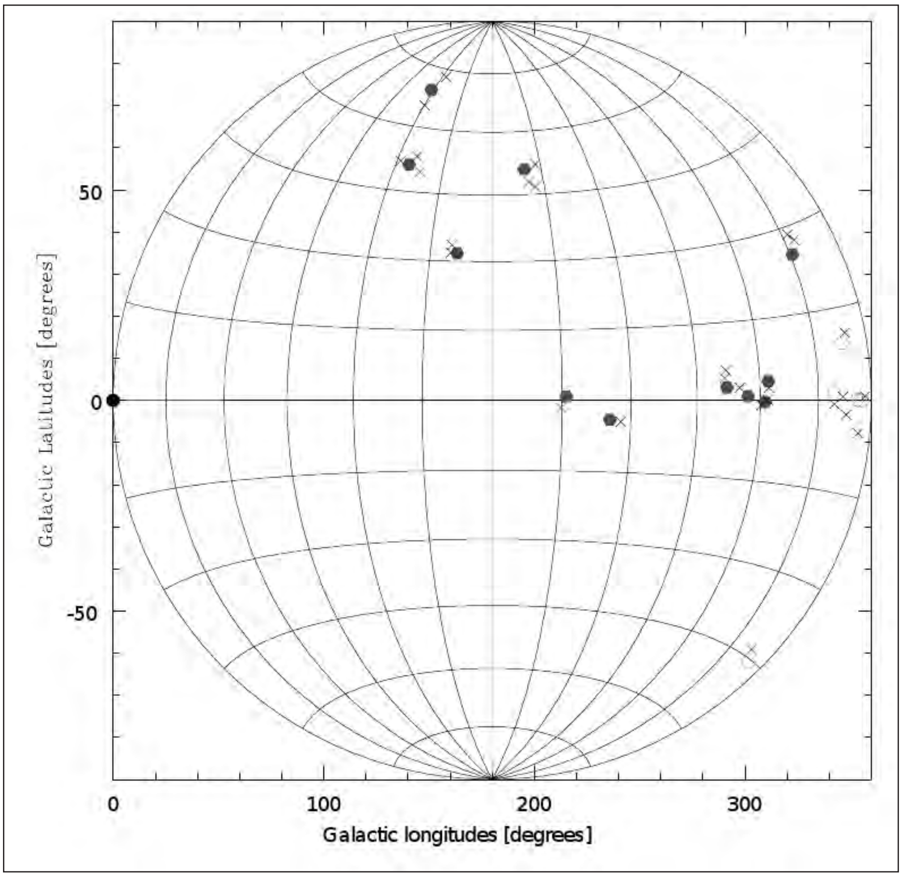

Fig. 4: Aitoff representation of galactic coordinates of VLBI best candidate PSR in red circle, of ICRF reference sources in blue cross and other possible PSR candidates.

Table 3: List of VLBI best candidate pulsars (indicated as PSR) and of ICRF reference sources in their vicinity (indicated as J). On line indicated PSR, the first column gives the official J2000 name of the pulsar, Columns 2 and 3 give respectively the J2000 right ascension and declination. Column 4 gives the flux observed by the NVSS (Han & Tian, 1999). Column 5 indicates if the pulsar was observed by NVSS or by Chatterjee (2004). On line with a first column beginning with a "J", information related to the closest ICRF reference sources are given. The first column give the J2000 ICRF-Ext.2 name of the source, Columns 2 and 3 give respectively the J2000 coordinates, and Column 4 gives the distance in degrees between the ICRF source and the pulsar.

PSR J0139+5814	01 39 19.77	58 14 31.8	4.0 ± 0.4	NVSS/C
J010245.7+582411	01 02 45.762383	+58 24 11.13664	4.799571	
PSR J0358+5413	03 58 53.70	54 13 13.6	10.3 ± 0.5	NVSS
J035929.7+505750	03 59 29.747262	+50 57 50.16150	3.257821	
PSR J0826+2637	08 26 51.31	26 37 25.6	17.1 ± 0.7	NVSS
J083052.0+241059	08 30 52.086185	+24 10 59.82046	2.602711	
J083740.2+245423	08 37 40.245686	+24 54 23.12172	2.979087	
PSR J1012+5307	10 12 33.43	53 07 02.6	4.5 ± 0.4	NVSS/C
J095738.1+552257	09 57 38.184490	+55 22 57.76914	3.142610	
J103507.0+562846	10 35 07.040267	+56 28 46.79733	4.674220	
J095622.6+575355	09 56 22.634451	+57 53 55.90445	5.299584	
PSR J1022+1001	10 22 58.05	10 01 54.0	3.5 ± 0.4	NVSS/C
J102556.2+125349	10 25 56.285332	+12 53 49.02220	2.956259	
J103334.0+071126	10 33 34.024287	+07 11 26.14780	3.864539	
J100741.4+135629	10 07 41.498080	+13 56 29.60093	5.407060	
PSR J1136+1551	11 36 03.30	15 51 00.7	21.2 ± 0.8	NVSS
J112027.8+142054	11 20 27.807260	+14 20 54.99142	4.051844	
J114505.0+193622	11 45 05.009035	+19 36 22.74139	4.326826	
PSR J1713+0747	17 13 49.52	07 47 37.5	8.0 ± 1.4	NVSS/C
J165809.0+074127	16 58 09.011464	+07 41 27.54075	3.884443	
J165833.4+051516	16 58 33.447348	+05 15 16.44446	4.563597	
PSR B1919+21	19 21 44.80	+21 53 01.8	6.0	C
J192559.6+210626	19 25 59.605360	21 6 26.162118	1.15085	
J193124.9+224331	19 31 24.916782	22 43 31.259057	2.10889	
J193510.4+203154	19 35 10.472910	20 31 54.154178	3.00675	
J194606.2+230004	19 46 6.251405	23 0 4.414187	4.99801	
PSR B1937+21	19 39 38.55	21 24 59.1	16.0	C
J192559.6+210626	19 25 59.605360	23 0 4.414187	2.77097	
J193124.9+224331	19 31 24.916782	22 43 31.259057	2.00306	
J193510.4+203154	19 35 10.472910	20 31 54.154178	1.37982	
J194606.2+230004	19 46 6.251405	23 0 4.414187	1.91866	
PSR B1952+29	19 54 22.58	29 23 17.90	8.0	
J195740.5+333827	19 57 40.549919	33 38 27.94333	4.30368	
PSR B2011+38	20 13 10.49	38 45 44.8	6.4	
J195928.3+404402	19 59 28.356628	40 44 02.09695	3.37591	
J200744.9+402948	20 07 44.944838	40 29 48.60402	2.04589	

forth column is the NVSS flux at 1.4 Ghz. The last column indicates if the pulsar was observed in NVSS (NVSS) or by Chatterjee (C). For the ICRF sources, the first column is the official ICRF denomination, the two following columns are the J2000 coordinates in ICRF and the last column is the distance in degrees from the PSR.

The proposal is done on a 18 cm basis, asking for a typical EVN array at 18 cm. As 73% of the sources have a flux smaller than 5 mJy, the technique of phase referencing will be used with an accuracy in the astrometry expected to be better than 10 mas.

One can find on Figure 4 a representation of the spatial distribution of the pulsars as VLBI best candidates as well as their associated ICRF reference sources. One may also found localizations of 5 supplementary candidates which agree with the emitted minimal flux and ICRF sources vicinity criteria but are not optimum in term of EVN visibility.

Link between the ICRF and the dynamical system through close approaches between quasars and planets: application to Jupiter

One of the most important goals still remaining to be done with respect to the ICRF is its link with the dynamical reference frame determined through the time coordinates and the trajectories of moving celestial bodies, such as the Moon, the Sun and the planets. In this chapter, we already have discussed the contribution of the Moon, from the LLR (Lunar laser Ranging) observations. In addition we have also investigated the above link through the close encounters between Jupiter and the quasars for the coming years, focusing on the period involving the future space mission GAIA and evaluating the corrections due to the relativistic deflection of quasars light around Jupiter (Souchay et al., 2007).

Statistically we found a substantial number of close encounters between Jupiter and the quasars recorded by the Véron-Cetty and Véron (2003) catalogue, during the interval 2005–2015. At total 232 close approaches phenomena were detected, with an angular distance not exceeding 10’ both for $\Delta\alpha \cos\delta$ and $\Delta\delta$ (Souchay et al., 2007). These close approaches concern not only Jupiter, whose the angular size as well as the relative important brightness might be a barrier for differential astrometry, but also its satellites trail, whose photocenters are determined with sub-pixel accuracy. Therefore differential determinations of distance between the satellites and the given quasar might be very useful to improve the position of Jupiter in the ICRF.

Moreover we have shown that in the case of grazing phenomena, the order of magnitude of the light deflection related to them is relatively big (16 mas in the best cases) in comparison with the expected GAIA precision in the determination of the coordinates of celestial objects, around 10 μas.

Linking the ICRF to frames at various wavelengths: the construction of the LQAC (Large Quasar Astrometric Catalog)

The link between the ICRF and other frames at various wavelengths appears as a major issue in the present and next decade, with the drastic increase of quasars recorded at various wavelengths, thanks to huge surveys such as the Sloan Digital Sky Survey (SDSS) and the 2dF redshift survey (2QZ). Any quasar is likely to be of interest to the densification of the ICRF or the link to the ICRF. Therefore to compile all the presently recorded quasars was one of our leading activities. This work is not so simple as it is supposed to be: the huge and always increasing number of quasars reckoned from various sky surveys and catalogues leads to a large quantity of data which brings various and inhomogeneous information in the fields of astrometry, photometry, radioastronomy and spectroscopy. Moreover the cross-identifications between quasars recorded in two or more catalogues is not straightforward, especially when the quality of determination of the celestial coordinates is not good. These problems were tackled in order to construct a new compilation of quasars, called LQAC (Large Quasar Astrometric Catalog) which gives for each object the equatorial coordinates, multibands photometry radio fluxes, redshift, luminosity distance and absolute magnitudes.

One of the specificity of the LQAC is to give a flag (from “A” to “L”), indicating the presence of each quasar in one of the 12 larger quasar catalogues, 4 ones obtained from VLBI surveys (with a very good astrometry at the level of the sub-millarcsecond), and 8 ones from optical surveys. These catalogues are ranged by decreasing accuracy and are as follows:

- [A] ICRF-Ext.2 (radio)
- [B] VLBA/VCS (radio)
- [C] VLA-0.15 (radio)
- [D] JVAS (radio)
- [E] SDSS (optical)
- [F] 2QZ (optical)
- [G] FIRST (radio)
- [H] VLA+0.15 (radio)
- [I] Hewitt and Burbidge (optical)
- [J] 2MASS (infrared)
- [K] GSC23 (optical)
- [L] B1.0 (optical)
- [M] Véron-Cetty and Véron (optical + radio), 2006

Note that the VLA catalogue has been voluntarily divided into two sub-catalogues, respectively with flags “D” and ”H”. The first one has an accuracy a priori better than 0”.15, the second one worse than this value.

Information, when available concern, in addition to the celestial equatorial coordinates with respect to the ICRF, the *u*, *b*, *v*, *g*, *r*, *i*, *z*, *J*, *K* photometry as well as redshift and radio fluxes at 1.4 GHz (20 cm), 2.3 Ghz (13 cm), 5.0 Ghz (6 cm), 8.4 Ghz (3.6 cm), and 24 Ghz (1.2 cm). The small proportion of remaining objects not reckoned in one of the 12 above catalogues are picked up from the Véron-Cetty and Véron (2006) compilation catalogue, with a number (instead of a letter) as a flag, indicating the original catalogue.

Our final LQAC catalogue contains 113 666 quasars, which is 33.4 % bigger than the number of quasars recorded in the last version of the Véron-Cetty and Véron (2006) catalogue, which was the densest compilation of quasars up to now. In the related paper (Souchay et al., 2008) we discuss the external homogeneity of the data by comparing the equatorial coordinates, the redshifts and the magnitudes of objects belonging to two different catalogues.

At last we used up-to-date cosmological parameters as well as recent models for galactic extinction and *K*-correction in order to evaluate at best the absolute magnitudes of the quasars. The cosmological model is based on a Friedmann-Lemaître-Robertson-Walker metric with a curvature of space *k* null, a deceleration parameter $q_0 = -0.58$ and a Hubble expansion factor $H_0 = 72$ km s^{-1} Mpc^{-1}. Notice that we evaluated the absolute magnitude of the quasars at two wavelengths, blue one (M_B) and infrared one (*Mi*).

The various steps in the construction of the LQAC are described in detail by Souchay et al. (2008) and the catalogue is already available in ASCII file at <ftp://syrte.obspm.fr/pub/LQAC/LQAC2008.ascii>.

Notice that the LQAC extended results have also been stored in Votable format compatible with Astronomy VO Data Format and VO tools like Aladin, Topcat, Voplot. This catalogue is more complete than the ASCII one. For instance we keep in this database all the original catalogue references and nominal values (with uncertainties), even when they are not unique, for each data field (magnitude, redshift, radioflux) of a given quasar.

Reductions of Mosaic-CCD observations at the CFHT and astrometric follow-up of artificial satellites

The link between the ICRF and the OCRF (Optical Celestial Reference frame) is a major goal in the very near future astrometry. It is also of great interest to link the ICRF with other frames like the dynamical reference frame. In order to achieve these tasks we have begun, since January 2007 to use the data, in FITS format, of the CFHT Legacy Survey (CFHTLS).

In a first step we have used the software provided by TERAPIX (<http://terapix.iap.fr/>), the astronomical data reduction center of the CFHTLS. This software package is mainly composed of three parts: Sextractor (<http://terapix.iap.fr/soft/sextractor>, a program that builds a catalogue of objects from an astronomical image), SCAMP (<http://terapix.iap.fr/rubrique .php?id_rubrique=105>, which reads Sextractor catalogues and computes astrometric and photometric solutions for any arbitrary sequence of FITS images in a completely automatic way) and SWARP (<http://terapix.iap.fr/rubrique.php?id_rubrique=49>, a program that resamples and co-adds together FITS images using any arbitrary astrometric projection defined in the WCS Standard, <http://fits.gsfc.nasa.gov/fits_wcs.html>).

In order to have a step by step control of this software, and to generate our astrometric solutions, we have build our own astrometric reduction software. Despite the fact that it is up to now under construction, it shows that we can obtain astrometric measurements with an uncertainty in the range of 50–100 mas. When the present developments will be achieved we plan to obtain an uncertainty of a few tens of mas or less. This is particularly of interest in the perspective of GAIA (<http://gaia.esa.int/science-e/www/area/index.cfm?fareaid=26>) because the limit magnitude achieve by CFH Telescope can reach V=25 or even V=28–29 in the Deep field programs (<http://terapix.iap.fr/rubrique.php?id_rubrique =108>). In comparison GAIA will achieve at best the 20th magnitude with an accuracy of 0.2 mas.

We are also trying to link together the 36 CCD of the MEGACAM mosaïc (<http://www.cfht.hawaii.edu/Instruments/Imaging/Megacam/>) used in the focal plane of the CFHT (<http://www.cfht.hawaii.edu/>). This specific software will be also useable with other CCD mosaïc like the WFI (<http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/WFI/>) of the ESO.

We have also carried out our own observations with the ESO 2.2m telescope, towards some deep fields of quasars. We also plan to regularly observe with the 2.0m telescope of the Observatoire du Pic du Midi (France, <http://bagn.obs-mip.fr/>) and with the 0.60m of the Belogradchik Observatory (Bulgaria, <http://www.astro.bas.bg/~aobel/equipment.html#60cm>). Of course we plan to use the 3.6m CFHT. We have submitted an observation program for the semester 2008A but it has not been retained by the QSO (Queued Service Observation, <http://www.cfht.hawaii.edu/Instruments/Queue/>) team during the phase 2 proposal submission. A new proposal will be submitted for 2008B.

Our under way projects are firstly about WMAP and secondly about the link between the magnitude variations and positions of the quasars in the sky. WMAP is a probe of the NASA that we want to observe to test the “GAIA tracking concept”. WMAP is located at the second Earth-Sun Lagrange point L2, about 1.5 million kilometres from Earth, just like GAIA will be once launched in a very near future. WMAP is consequently a reasonable photo-model for the brightness and observability of GAIA. In consequence we have launched a program to observe WMAP with an optical telescope and to see if it is possible to monitor it’s position and velocity with an uncertainty of 150 m and 2.5 mm/s respectively. If so, then the scientific goal of GAIA will be achieved, that is to say the correct evaluation of GAIA’s position measurements. Some observations of WMAP (<http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42754>) have already been achieved with WFI at the ESO.

The second project under study i.e. the detection of correlation between the astrometric and photometric variability in quasars, is prepared in collaboration with the Rio observatory, and will be presented during the SAB’08 meeting (<http://sab08.org/>).

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