Celestial Reference Frame Issues

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1 IERS responsibilities with respect to the ICRF

According to the recommendations of the IAU (International Astronomical Union) the IERS has the responsibility of monitoring the ICRS (International Celestial Reference System), and maintaining its current realization, the ICRF (International Celestial Reference Frame). These activities are run jointly by :

- the ICRS Center of the IERS
- the IVS (International VLBI Service for Geodesy and Astrometry)
- the IAU Working Group on the International Celestial Reference System

1.1 Maintenance of the ICRF (IVS / ICRS Center)

- Since January 1, 1988 the Celestial Reference Frame recommended by the IAU is based on a set of extragalactic directions, replacing the FK5 (Fifth Fundamental Catalogue). While the FK5 gave coordinates of galactic objects (stars) in a reference system based primarily on the dynamics of the solar system (the so-called equator and equinox of J2000.0), the definition of the ICRS is based on a kinematical concept, according to which the axes of the system remain fixed with respect to the most distant matter of the universe.
- According to the rules adopted in the 1991 IAU Recommendations, the fundamental directions of the celestial reference system will remain fixed in space, as long as the directions of the distant sources can be globally considered as fixed directions. The adopted positions of the defining sources may be re-estimated when improved information is available, but the direction of the coordinate axes will be maintained by implementing the statistical condition that the new coordinates of selected sources show no global rotation with respect to the old set (no-rotation condition). It is also foreseen that some sources may be deleted or new ones could be added in the future. This is the purpose of the maintenance of the ICRF.
- The initial ICRF realization consisted of equatorial coordinates of 608 extragalactic radio sources derived from about 1.6 million observations accumulated by a worldwide network over 1979–1995. It was derived by a sub-group of the WGRF that agreed on an optimal data analysis strategy (Ma et al., 1998, AJ 116, 516). It included three categories of objects, with
  - the most compact and best observed 212 defining sources, with a median uncertainty of 0.4 mas on individual positions,
  - compact sources (294) whose positions were likely to be improved when more observations would be accumulated in the future, and
  - sources less appropriate for astrometric purposes (102), but which were provided for possible ties of reference frames at other wavelengths or for other objectives.

The ICRF was obtained by a global single analysis of all VLBI observations available at the time of computation. The source selection and analysis strategies applied were discussed by the team of co-authors of the ICRF.

- In the following are the rejection criteria which were adopted for the selection of extragalactic sources for the ICRF:
  - Arclength formal error > 1 mas
  - < 20 observations
  - < 2-year span of data
  - 3 σ or > 0.5 mas discrepancy between catalogues
  - Excessive structure
  - Large, significant "apparent motions"
  - Arc source, i.e., position adjusted for each session.
- Several sources have been rejected since 1998.

1.2 ICRF-Ext.1 (1999): results of a 5 years maintenance (1994–1999)

The ICRF-Ext.1 was constructed on the basis of five years of additional observational data spanning December 1994 through April 1999 (600 000 observations, 461 sessions). The list and coordinates of the defining sources were not changed (although it was found that some of them showed discrepant positions). The coordinates of the candidates and other sources were refined. 59 new sources were added to the frame, bringing the total number to 677. In addition to the consideration of new observations, some improvements were brought in the analysis models, including :

- Tropospheric mapping function
- Troposphere linear interval
- Subdiurnal EOP
- Fixed station axis offsets
- Added noise for each session

1.3 Comparisons of catalogues via ICRF

The relative orientations between individual celestial reference frames established by individual teams (BKGI, GSFC, IAA, SHA), and the ICRF are regularly determined through the rotation angles which transform coordinates from the individual VLBI frames to ICRF. They are calculated on the basis of the defining sources only.

- Rotations : three rotation angles around each of the rectangular axes of the ICRF are estimated. They are typically of the order of a few μas or a few tens of μas.
- Slopes and bias: slopes defined in function of the right ascension and the declination, biases in function of the declination are estimated for checking purposes. They are usually statistically insignificant.

1.4 Link with the dynamical frame (LLR)

- Aim: position of the inertial dynamical ecliptic at a given epoch (J2000.0)
- This link requires the combination of various components
  - Moon's libration ephemerides (Celestial Mechanics)
  - Moon's orbital ephemerides (Celestial Mechanics)
  - Earth's nutation (VLBI)
  - ITRF (VLBI, GPS, SLR, DORIS)
  - Selenocentric coordinates of lunar stations.

1.5 Check of the celestial pole offsets (VLBI)

- **Combination** of VLBI data with precession-nutation theory (IERS1996, MHB2000)
- Aim: periodical check (Annual Report) of the offset between the mean pole at J2000.0 and the ICRS pole.

- Involves
  - An up-to-date theory of the precession-nutation of the Earth (MHB 2000 replacing IERS, 1996)
  - VLBI time series of the celestial pole offsets $d\psi$, $d\varepsilon$.
- Results :
  - Sensitivity to the nutation model used (1–2 mas difference between the estimations of the pole offsets in $d\psi$, and $d\varepsilon$, when using one or the other theory above.
  - Sensitivity to the catalogue used, IERS-Ext.1 or individual solutions (BKGI, GSFC, IAA, SHA etc…)

1.6 Link to Hipparcos and other frames

This link is maintained through programs of densification at optical wavelengths (UCAC project of the USNO, Carlsberg Meridian Circle Program etc…). 2MASS (2 Micron All Sky Survey) recent release is available in order to make the link with Hipparcos Catalogue.

2 Present status in the field

2.1 ICRF catalogue

- Condition of no rotation of the ICRF well verified
- Confirmation of possible improvements by taking into account the stability of source coordinates

2.2 Links

- Densification programs very active (2MASS, UCAC etc…)

3 Problems and deficiencies encountered

3.1 Rationale for a revised ICRF

- In 2002 over 3.2 millions observations of over 700 sources are available. This is twice the number of observations used for the initial ICRF. It was shown (Gontier et al., 2001, A&A 375, 661) that, as results of the steady improvement of the observing conditions by the world astro-geodetic VLBI network, the radio source coordinates become much more stable and reliable towards the end of the 1980s. The 15 years of observations used for the initial ICRF can therefore be expected to be of much lower value than those accumulated during the most recent 12–15 years.
- The influence of time stability of the radio-source directions on nutation determinations was investigated in parallel to the study of atmospheric perturbations to the astronomically driven precession and nutations (Dehant et al., 2003, JGR 108, B5). The effect was found to become negligible at the seasonal and free nutation periods after 1990. For the precession correction and the obliquity rate, the 9.3 year nutations and the 18.6 year nutations, the effect reaches 10–30 microarcseconds, a level that is not negligible when compared to the observed discrepancies between VLBI results and the IAU2000 precession-nutation model, that may reach nearly 100 microarcseconds. This result shows that the role of the celestial reference frame stability is worth analysing in a rigorous way if further progress is sought in the measurement of the Earth's precession and nutation.
- Another study presented at the 2002 IERS Analysis Workshop and later published (Feissel-Vernier, 2003, AA 403, 105) concludes that a selection process based on the time stability of directions of individual radio-sources strengthens the no-net rotation, condition and improves the internal consistency of the frame.

3.2 Other points:

- The VLBA Calibrator Survey (VCS1) added ~1200 new sources to the astrometric catalogue north of –30 deg, but the observing schedule was unlike the usual astrometric/geodetic mode. (Beaseley et al., 2002, ApJ Sup 141, 13)
- Requirement for a clear explanation of the rotations between individual celestial catalogues, and of their discrepancies concerning the coordinates of the extragalactic sources, in order to optimise in the future the extension of the ICRF.
- Proposition to make a combined catalogue in parallel to the ICRF or possibly replacing it in the future. This proposition might be discussed.
- Although the true pole of any observed date is now measured with a precision better than 0.1 mas, the celestial pole offset (direction of the mean pole at J2000.0 in the ICRS) is highly dependent on the observational data and of the precession-nutation model used. Its determination could be ameliorated by a specific weighting of the estimations.
- Proper motions of quasars (or motion of their photocenter) are supposed to be null or negligible (one of the postulates in the construction of the ICRF). Simulations based on relativistic formulas show how tangential displacement can be enhanced in the case of high-speed velocities.

3.3 Possible discussions

- New discussion of the parameter selection and modelling in the analysis
- Selection of the observation span and of the sources to be considered for applying the no-net rotation condition to the initial ICRF
- Considering the global character of the CRF-EOP-TRF products
- Method of computation, e.g. unique global analysis vs comparison/combination of several global analyses
- Reassessment of the tie of celestial frames available in the optical wavelength (Hipparcos etc…)

4 Goal and future steps for improvement

- The IVS is designing the future CRF observing program to improve the astrometric data set, particularly by increasing astrometric observations in the southern hemisphere and by targeting sources to fill gaps and to provide more information about the prospective defining sources. In addition observations using the VLBA have begun to create a frame at higher frequencies.
- An **overwhelming change** in the definition of the ICRF is expected with the future Space missions; a new ICRF defined optically may be constructed in the future on the basis of very promising results through space observations programs:
  - FAME (Full-sky Astrometric Mapping Explorer), but NASA has withdrawn funding
  - SIM (Space Interferometry Mission), finishing Phase A
  - GAIA, confirmed and scheduled for not later than 2012
- Concepts for the future ICRF
  - **problem of the continuity**: will all the quasars included in the present ICRF be observed by the future astrometric space missions?
  - will the « ICRF of the future » be a dual catalogue (cross-identifications radio-optical) or a pure optical one?

5 Schedule of the next steps and concrete recommendations

- **Experimentation** of a combined catalogue to be compared with the ICRF (as BKGI)
- **Construction of a « rigorous combination »**
  - simultaneous adjustment of the ITRF, the EOPs, and the ICRF, producing a fully consistent set of ITRF site coordinates and velocities, EOP series, and ICRF coordinates.
- **Preparation** of the future space missions