PART I

VLBI GLOBAL ASTROMETRY
THE CONTRIBUTION OF VLBI
TO THE REALIZATION OF A CELESTIAL REFERENCE SYSTEM

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INTRODUCTION

Observations of celestial bodies, whether natural or artificial and including the Earth itself, can be used to describe motions only if they can be referred to a system of coordinate axes that are assumed to be fixed in space, or that have well known time variations with respect to something else that is fixed. These fixed axes are referred to as a celestial reference system. To make possible the comparison of results obtained in various fields, it is advantageous to adopt conventionally one definition of the celestial reference system. These coordinate axes can only be accessed indirectly through coordinates of a set of fiducial objects. Such a set of coordinates is referred to as a celestial reference frame.

The fixed directions underlying the FK5 (Fricke et al., 1988) and the preceding fundamental star catalogues of positions and proper motions were defined from the dynamical modeling of the Earth's orbital motion (ecliptic, equinox). In the past, these fundamental directions were considered conventional for some decades; they were changed from time to time, in particular to take advantage of advances in modeling of the motion of solar system objects. In its 1991 Recommendations on Reference Systems (Bergeron, 1992; see also Guinot, 1979; Kovalevsky and Feissel, 1996), the International Astronomical Union (IAU) decided to select distant extragalactic objects as the basis of its new celestial reference system and to adopt directions that would be fixed with respect to a selected set of these objects. These directions would be consistent with their previous realizations, i.e., the FK5 right ascension origin and pole, within the uncertainties of the FK5. A fundamental advantage of selecting extragalactic objects is that they are so distant that their proper motions are undetectable, even by the most precise present techniques.

In order that the use of this new reference system not be detrimental to the analysis of the highly accurate astrometric techniques, the IAU explicitly introduced the Theory of General Relativity as the background for all theoretical and data analysis problems related to time and space.

According to the adopted new rules, the fundamental directions of the celestial reference system will remain fixed in space; they will no longer be dependent on modeling the motion of solar system objects. The fiducial objects will be monitored. The adopted positions 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 coordinates of selected defining sources show no global rotation from the old set of coordinates to the new one.

The choice of extragalactic objects to realize the fiducial directions was made possible by the availability of a mature and highly precise observing technique, Very Long Baseline radio Interferometry (VLBI). The purpose of this IERS Technical Note is to describe how VLBI is used to define and maintain a celestial reference system that follows the 1991 IAU Resolutions on Reference Systems.

THE INTERNATIONAL CELESTIAL REFERENCE SYSTEM (ICRS)

The ICRS (Arias et al., 1995, see also Part IV, this volume) was defined by the International Earth Rotation Service (IERS). It is expected to be adopted in 1997 by the IAU as the primary celestial reference system, replacing the FK5. It complies with the conditions specified by the 1991 IAU Recommendations. The Hipparcos star positions and proper motions and the JPL solar system ephemerides (starting with DE403) are already expressed in the ICRS. The origin of the ICRS axes is located at the barycentre of the solar system. For the sake of continuity with the FK5 system, the ICRS pole is in the J2000.0 direction defined by the conventional IAU models for precession (Lieske et al., 1977) and nutation (Seidelmann, 1982). The origin of right ascensions is also defined consistently with that of the FK5 by fixing the right ascension of 3C 273B to the Hazard et al. (1971) FK4 value transformed to J2000.0.

Adopting extragalactic directions as primary celestial references has been considered for over a decade by the IAU. A series of Working Groups was organized jointly by several IAU astrometry commissions mainly to establish lists of appropriate objects. A decisive breakthrough was the codification by the Working Group on Reference Systems (1988-1991) of a comprehensive group of Recommendations (see section IV, this volume) that dealt with both the fundamental concepts of space-time references and their actual realizations. During the 1991-1994 term, the IAU Working Group on Reference Frames (WGRF) established a list of about 600 radio sources that would be used to realize an extragalactic celestial reference system. Meanwhile, the IERS had initiated and developed an operational process to maintain the celestial reference system. During the 1994-1997 term, the WGRF will conclude this long preparation by presenting for adoption by the 1997 IAU General Assembly a recommendation for the adoption of the ICRS and the future maintenance of the ICRF (International Celestial Reference Frame) by the IERS, assisted by an IAU advisory group.

VERY LONG BASELINE RADIO INTERFEROMETRY

History

VLBI is the only technique that provides simultaneous estimations of directions of extragalactic radio sources (quasars, galactic nuclei, ...), of terrestrial coordinates of observing sites and of the Earth's orientation.

The first development of VLBI, however, was motivated by its potential for radio astronomy. The history of radio astronomy dates from 1929 when Karl Jansky, a radio engineer, began looking at radio signals with decametric wavelengths which he found were associated with the centre of the Galaxy (Jansky, 1933, 1935). A few years later, Grote Reber further studied these emissions and published the first radio map of the sky (Reber, 1944). Research projects were started in radio astronomy in Australia and in Great Britain after World War II. Larger antennas were built and the first attempts were made to get finer resolution on the sky by using interferometry. These experiments were used to derive radio source catalogues, e.g., the 3rd Cambridge Catalogue (Edge et al., 1959), and to identify optical counterparts (Bolton et al., 1949; Baade and Minkowsky, 1954). Bright compact sources were discovered in the course of these studies.

By the early 1960's, the development of connected-element interferometry, where the signals received by the two antennas are transmitted by cable to be referred to a single clock, had brought the interferometric resolution of observations to a few arcseconds. However, at that time, several independent investigators had concluded that sources with much finer structure were likely to exist that could not be resolved by the longest connected baseline, Jodrell Bank-Malvern (127 km, connected via a radio link). It became clear that understanding the physics of galactic nuclei and quasars made it necessary to reach an angular resolution of 0.001" (one milliarcsecond, mas), i.e., the length of baselines had to be extended to thousands of kilometres. The signals at the two antennas could no longer be referred to the same clock, which put tight constraints on the stability of the station clocks. At about the same time, new commercial atomic time clocks with a stability of $10^{-12}$ became available. Two groups, in Canada and in the USA, developed an unconnected interferometric technique: the signals are recorded and dated separately on magnetic tapes at the two stations, the tapes being
shipped to a specialized computing centre where the signals are correlated. The first successful VLBI measurements, with a few hundredths of an arcsecond resolution, were obtained in 1967 (Broten et al., 1967; Bare et al., 1967).

The use of VLBI has proceeded in two general directions divided by the type of VLBI observable used. On one hand, VLBI continues to provide maps of the detailed structure of celestial objects using interferometric amplitude and phase information. This is the most common astrophysical application. The 10-antenna VLBA (Very Long Baseline Array) is the premier instrument designed specifically for such work, while international consortia such as the EVN (European VLBI Network) organize VLBI observations using arrays of existing observatories. The other face of VLBI is the precise measurement of celestial and terrestrial positions using the delay and delay rate observables, described below. The first VLBI astrometry reported in 1971 (Cohen and Shaffer, 1971) was no better than a few arcseconds. Global VLBI astrometric and geodetic programs were begun in the 1970's for the study of the Earth's rotation, for referencing solar system probe trajectories to inertial space and for monitoring tectonic plate motions and regional deformation. By the mid 1980's astrometric precision had improved to a few milliarcseconds (Fanselow et al., 1984; Ma et al., 1986). VLBI was a major participant in the IAU/IUGG MERIT Program (1978-1987), then in the IERS since its creation in 1988.

**Applications to global astrometry and geodesy**

VLBI (Fig. 1) is a geometric technique that measures accurately directions in space. Using a pair of distant antennas, the difference in the time of arrival at the two stations of signals emitted by the same radio source is measured with a precision of a few picoseconds. (Light travels one mm in three picoseconds). This time difference (delay) and its first time derivative (delay rate) are reconstructed by offline correlation of the signals recorded at the two ends of the baseline.

A key piece of equipment at the stations is the clock against which the events are dated. As the received signal is typically broadband noise, the reference time scale delivered by the clock must be extremely stable in the short term. VLBI makes use of the most stable frequency standards in the short term, i.e., hydrogen masers that have a stability of $10^{-14}$ over 1000 seconds.

The frequency bands used in astrometric and geodetic applications are the S and X bands, with respective frequencies 2.3 and 8.4 GHz and wavelengths 13 and 3.6 cm. The signals are recorded under the Mark III protocol (Rogers et al., 1983), but VLBA format has also been used.

The observing strategy aims at obtaining estimates of the desired global parameters that are not contaminated by poor determination of the ancillary local parameters that are necessary to consider in the data analysis. A typical observing session involves 6 to 21 terrestrial baselines observing a few tens of extragalactic radio sources over a 24-hour time span, producing several hundred to several thousand observations (delay and delay rate). The analysis consists of a least squares estimation of global parameters that describe the direction of radio sources and the position and motion of the observing stations, the Earth's orientation, and local parameters used to model the station behaviour and environment. Whereas the local and Earth orientation parameters are determined for each session, getting the radio source and station parameters requires the stacking of a number of observing sessions. An important aspect of the analysis is the use of state-of-the-art standards and models, such as the IERS Conventions (McCarthy, 1996).

The celestial reference frame results presented in this Technical Note are based on essentially all of the observations accumulated over about 15 years in several worldwide programs. Dual frequency Mark III data have both geodetic and astrometric applications. Most of the data (95% of nearly 2 million observations) were acquired primarily for geodetic purposes. The major geodetic programs include: NASA's Crustal Dynamics Project and Space Geodesy Program for plate tectonics, regional deformation and high resolution determination of the Earth Orientation Parameters (EOP); the International Radio Interferometry Surveying (IRIS-A), the program of the US Naval Observatory (USNO), NAVNET, and their successor NEOS for regular monitoring of EOP; the European and IRIS-S efforts organized by the Bonn Geodetic Institute; and USNO's NAVEX sessions for the terrestrial reference frame. The geodetic programs have used the brightest radio sources, gradually concentrating on the most compact as sensitivity improved. These geodetic sources are also the foundation of astrometric work because of the large number of observations for the ~150 most commonly used. The
astrometric programs which densify the sky include the Radio-Optical Reference Frame sessions done by US Naval Research Laboratory (NRL) and USNO and the space navigation efforts of Jet Propulsion Laboratory (JPL). More than 60 antennas distributed on all continents and several islands have participated including fixed stations ranging in size from 12 to 100 m in diameter as well as three small mobile VLBI systems. The numbers of observations per program used for the ICRF analysis are given in Table 1. The networks of baselines in the major programs are shown on Figure 2. The number of sources observed by various groups of observing programs is given in Table 2.

Figure 1. The principle of VLBI observations
(Drawing by John Hazen)
VLBI DATA ANALYSIS

A detailed description of astrometric and geodetic VLBI analysis is given by Sovers and Jacobs (1996). We summarize hereafter the most critical aspects that influence the construction of celestial reference frames.

**Global modeling and parametrization**

The astronomical modeling of observations entails expressing as a function of time the transformation between the celestial reference frame, materialized by the extragalactic radio source directions, and the terrestrial reference frame, materialized by the observing station coordinates. The terrestrial reference frame is rotating and orbiting around the Sun. The background theory is General Relativity, as recommended by the International Astronomical Union (see Section IV, this volume).

The global parameters are estimated as corrections to a priori parameters used to calculate approximate values of the observables, delays and delay rates. These parameters are as follows.

**Celestial reference frame:** equatorial coordinates (right ascension, declination) and in some cases their time derivatives, expressed in a reference system whose origin is at the barycentre of the solar system. A core of defining sources is assumed to have globally no rotation in inertial space.

**Terrestrial reference frame:** Cartesian station coordinates and their time derivatives, expressed in a reference system whose origin is at the Earth's centre of mass. The secular motion due to tectonic plate drifting (1 to 10 cm/year) is taken into account either by a model or, when observations are strong enough, as estimated parameters.

**Earth orientation:** Greenwich sidereal time, coordinates of the pole in the celestial and the terrestrial reference frames, and in some cases their time derivatives. The Earth orientation parameters are determined independently for each observing session. Omitting the direct estimation of the celestial pole coordinates (also called nutation offsets) in the analysis, i.e., relying on standard precession and nutation models, would give rise to random and systematic errors at the level of several mas. In fact, VLBI is the most precise and accurate technique that can be used in the investigation of nutation and precession (see, e.g., Souchay et al., 1996).

The major sets of software in use for this modeling have been intensively tested and intercompared. They are considered to be consistently implemented within one picosecond for the delay and one femtosecond/second for the delay rate, one order of magnitude better than the observations. While the software implementation has been carefully checked, the model parameters required by the software are not known well enough to produce a model that is accurate to better than a few tens of picoseconds.

However, as the space-time geometry of observations can never be fully uniform relative to the global parameters, errors in the estimations, both random and systematic, may be expected. These limitations have to be taken into account when estimating realistic uncertainties for the results.

**Local modeling and parametrization**

The local parametrization concerns the modeling of effects that are attached to the celestial objects or to the observing stations.

Local effects considered for the celestial objects are associated with asymmetric or time-evolving geometric structure of the radio sources that may produce apparent displacements when observed with baselines of different lengths (hence with different resolution of the source), or as the emission barycentre moves in the structure. If maps of a source are available, astrometric corrections can be made to always refer the source direction to the same conventional fiducial point in its structure (Charlot, 1990; Fey and Charlot, 1997). Other effects, such as transient gravitational lensing, may be present and would also give rise to spurious source motions. All these effects can amount to a few tenths of mas/year (Eubanks et al., 1995).
### Table 1. Observations used for ICRF: counts (in thousands) by time span and program

<table>
<thead>
<tr>
<th></th>
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<td>CDP</td>
<td>23.7</td>
<td>67.4</td>
<td>110.6</td>
<td>75.6</td>
<td>277.4</td>
<td></td>
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<td>POLA</td>
<td>24.8</td>
<td></td>
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<tr>
<td>MOBL</td>
<td>6.5</td>
<td>40.6</td>
<td>79.5</td>
<td>28.6</td>
<td>155.2</td>
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<td>IRIS-A</td>
<td>77.5</td>
<td>91.2</td>
<td>144.8</td>
<td>18.2</td>
<td>331.7</td>
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<td>GSI</td>
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<td>1.0</td>
<td>2.3</td>
<td>.2</td>
<td>3.8</td>
<td></td>
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<tr>
<td>IRIS-S</td>
<td>1.7</td>
<td>6.4</td>
<td>23.6</td>
<td>16.7</td>
<td>48.4</td>
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<td>14.3</td>
<td>6.1</td>
<td>30.2</td>
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<td>USNO</td>
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<td></td>
<td></td>
<td>1.7</td>
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<td>NAVNET</td>
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<td>14.0</td>
<td>75.8</td>
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<td>95.7</td>
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<td>4.1</td>
<td>.6</td>
<td>5.3</td>
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<td>8.7</td>
<td>11.6</td>
<td>20.4</td>
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<td>EUR</td>
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<td>18.0</td>
<td>26.8</td>
<td>44.8</td>
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<td>GERMAN</td>
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<td>.9</td>
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<td>29.4</td>
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<td>SGP</td>
<td>50.6</td>
<td>301.6</td>
<td>352.2</td>
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<tr>
<td>VLBA</td>
<td>3.2</td>
<td>4.9</td>
<td>8.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEOS-A</td>
<td></td>
<td></td>
<td>103.2</td>
<td>103.2</td>
<td></td>
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<tr>
<td>NEOS-B</td>
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<td></td>
<td>19.9</td>
<td>19.9</td>
<td></td>
<td></td>
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<tr>
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<td>6.1</td>
<td>11.2</td>
<td>9.3</td>
<td>26.8</td>
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<td>22.5</td>
<td>22.5</td>
<td></td>
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<tr>
<td>DSN</td>
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<td>10.0</td>
<td>3.1</td>
<td>13.6</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>55.2</td>
<td>187.6</td>
<td>325.2</td>
<td>499.9</td>
<td>579.9</td>
<td>1647.8</td>
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</table>

The explanation of the acronyms is given in Appendix, p. I-14.

### Table 2. Number of ICRF radio sources observed by various groups of VLBI programs

<table>
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<tr>
<th>Program grouping</th>
<th>Purpose</th>
<th>Number of sources</th>
<th>Baselines</th>
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<tr>
<td>DSN</td>
<td>navigation, astrometry</td>
<td>281</td>
<td>2</td>
</tr>
<tr>
<td>CDP/SGP</td>
<td>survey, astrometry</td>
<td>368</td>
<td>77</td>
</tr>
<tr>
<td>NRL</td>
<td>astrometry</td>
<td>518</td>
<td>85</td>
</tr>
<tr>
<td>CDP/SGP</td>
<td>geodynamics</td>
<td>138</td>
<td>524</td>
</tr>
<tr>
<td>USNO/NAVNET/NAVEX</td>
<td>EOP, terrestrial reference frame</td>
<td>196</td>
<td>223</td>
</tr>
<tr>
<td>POLA/IRIS/NGS/NEOS</td>
<td>EOP</td>
<td>172</td>
<td>224</td>
</tr>
<tr>
<td>all others</td>
<td>geodesy</td>
<td>76</td>
<td>180</td>
</tr>
</tbody>
</table>
Figure 2. VLBI stations used for observing ICRF radio sources. The sets of baselines that collected 80% of observations in each of the groupings of programs in Table 2 are shown.
The terrestrial and environmental local effects are quite complex. They include tidal crustal motions, perturbation of the signal transmission through the ionosphere and the troposphere, and the station equipment.

Vertical and horizontal tidal motions (solid Earth tides with an amplitude of tens of cm, ocean tide loading effects with amplitudes of the order of one cm) are modeled with an accuracy of one mm by the IERS Conventions. Note that the VLBI analyses can also be exploited to test and improve these models.

The ionospheric delay to first order is inversely proportional to the squared frequency of the transmitted signal. This effect is eliminated by the use of two frequencies (S and X band), as done classically in radio-frequency work. The tropospheric delay is partially modeled by a conventional model that maps the delay as a function of the elevation of observations (i.e., the length of the path of the signal in the troposphere). The zenith delay due to the dry component of the troposphere is around 7 nanoseconds and can be predicted to -0.01 ns. That due to the wet component is smaller (<1 ns) but is poorly calibrated (~0.2 ns) from humidity. Calibrating it better would require knowledge of the water vapor content along the line of sight that may vary in time and azimuth during the session. The classical treatment of the effect is the estimation of the zenith delay using a conventional elevation-like mapping function for short time intervals (minutes to hours). An additional refinement is to parametrize and estimate the azimuthal dependence of the delay (gradient parameters). The correction of the tropospheric delay is currently the major modeling error in astrometric and geodetic VLBI.

Last but not least, the station clocks and electronic devices that are used from the receiver horn through the tape recorder introduce drifts and irregularities in the timing of the observations that are sent to the correlator. The clocks are generally synchronized within about one microsecond. The differential behavior of the timing devices is further modeled for each station, generally as piecewise time-linear segments, with sets of biases and drifts estimated from the observations. The numerous experiments performed on this part of the modeling have led to computational practices which seem to be harmless to global astronomical and geodetic parameters.

ERROR BUDGET OF VLBI-DERIVED CELESTIAL REFERENCE FRAMES

Global astrometric and geodetic VLBI as implemented since the early 1980's allows the construction of a global celestial reference frame that is accurate to better than 0.5 mas. The many improvements brought along the years to the observing programs and to the analyses (see the list of bibliographic references p. 1-15) have continuously decreased the level of random and systematic errors. The level currently reached can be estimated by intercomparison of VLBI celestial reference frames obtained with various analysis strategies and modeling options. These experiments give a measure of the interaction of mismodeling with imperfect time-space geometry of observations. Their results are illustrated on Figure 3. The two identified main causes of remaining problems are as follows.

- Modeling the variations in the wet troposphere delay as a function of elevation, time and azimuth is the most deficient part of the analysis, with random and systematic effects of the order of 0.1-0.3 mas. Alternate approaches that have been studied consider additional in situ measurements, either with water vapor radiometers that measure directly the vapor content along the line of sight, or with results from analysis of collocated GPS stations. The work presented in this Technical Note used a recent improvement of the modeling that estimates an azimuthal dependence of the tropospheric delay (gradient correction, McMillan 1995). It is expected to remove systematic errors at the level of 0.3 mas and random ones at the level of 0.1 mas.

- The consideration of source structure, or source apparent motion, with random and systematic global effects at the level of 0.3 mas for the sources selected for astrometric work. In the implementation of the ICRF, all sources with detectable apparent motion were excluded from the set of defining sources.

The item labeled 'Baseline vector status' in Figure 3 may be taken as a rough estimate of remaining global analysis errors. It is at the level of 0.1 mas, clearly random. In principle, provided that coseismic and accidental station displacements are accounted for, a time-linear model for the
behaviour of the baselines is considered appropriate. When analyzing observations spanning many years and using more or less intensively observed baselines, the use of this model represents quite a strong constraint on the global solution. The unavoidable correlations between the estimated parameters may propagate into the coordinates of the extragalactic source errors coming from other parts of the modeling and analysis. Therefore, analysis strategies aiming primarily at astrometric results may consider the baseline vectors as local parameters, i.e., parameters that are estimated for each session.

![Diagram of random and systematic errors in VLBI celestial reference frames.](image)

**Figure 3.** Random and systematic errors in VLBI celestial reference frames. Evaluations are based on the perturbation of analysis strategy with real data. The strategy retained in the implementation of the ICRF eliminated the sources with apparent motion from the list of defining sources and used an azimuth-dependent troposphere modeling that corrects most of the related systematic error.
GENERAL PROPERTIES OF VLBI EXTRAGALACTIC CELESTIAL REFERENCE FRAMES

The metrological characteristics of the VLBI-derived extragalactic reference frames result from the observing technique itself, from the objects that are selected for this application, and from its actual implementation and analysis.

Because VLBI observes in the microwave region of the electromagnetic spectrum, it is relatively insensitive to differences between day and night observing. This is in contrast to ground based optical observations which have large changes in detection sensitivity from day to night. Furthermore, microwave observations are relatively insensitive to the weather (clouds, rain) compared to ground based optical observations. These advantages have allowed VLBI to observe the full 24 hour range of right ascensions within a single experiment. This avoids the need to patch together observations from various parts of the sky and thereby reducing the potential for zonal errors.

Although VLBI is an Earth-based technique, it shares more observational and analysis characteristics with a space astrometry program like Hipparcos than with classical transit circle work. In addition to the impressive improvement in precision, the whole approach itself is a large step forward. The so-called fundamental astrometry made use of observations of stars and planets by isolated instruments. In practice, each program would define its own celestial system. The fundamental catalogue (last issue: FK5) was reconstructed as homogeneously as feasible from tens of these local catalogues. The computational means available to the astronomers made it impossible to analyze globally the complete data set, but this process was nevertheless a way to make available reference coordinates in a unique celestial reference system. The FK5 is a stellar realization of a dynamical reference system attached to the solar system. Its compilation was dependent on key models, such as those for precession, nutation and galactic rotation, and the tie of the star coordinates and proper motions to the fundamental directions in the solar system remained indirect.

From the Hipparcos continuous scanning of pairs of galactic directions, one constructs a rigid sphere of positions at some epoch as well as a system of highly homogeneous proper motions of galactic stars. Analyzing the entire data set provided by VLBI observations from a global Earth coverage of baselines that are operated in daily sessions over the years, one constructs directly a rigid sphere of extragalactic fixed directions. The analysis is completely redone as more data become available, physical models and estimation methods are improved, and new VLBI instrumentation is deployed.

With VLBI, each separate day of data gives the relative positions of the sources observed with some uncertainty. Adjusted nutation offsets for each day free the source coordinates from errors in precession/nutation. On different days different sets of sources are observed. It is the overlap of some common sources from one day to another that connects the positions together. From all the overlaps and directly measured relative positions comes the complete catalogue. Repeated measurements of relative positions, either directly in a day or indirectly from different days, improve the precision of the inferred positions. Varied combinations of baselines and of sets of observed sources improve the overall geometry and weaken the correlations of the source coordinates with the numerous phenomena modeled in the analysis.

Provided that observations are continued at a sufficient level, VLBI is fully capable of maintaining a set of highly stable directions referred to the most distant objects in the known universe to serve as a reference for all other sets of directions in the Galaxy, in the Solar System or on the Earth.
REFERENCES


Appendix: Explanation of acronyms in Table 1.

- **APT** Asia-Pacific Telescope
- **CDP** Crustal Dynamics Project - NASA
- **CRF** Celestial Reference Frame - NASA, USNO
- **CRL** Communications Research Laboratory, Japan - Pacific
- **DSN** Deep Space Network - astrometry
- **EUR** European geodesy - organized by Geodetic Institute, Bonn
- **EURMOB** European mobile
- **GERMAN** a few sessions between Germany and Asia
- **GSI** Geodetic Survey Institute, Japan - various places with transportable dish
- **IRIS-A** NOAA - EOP monitoring
- **IRIS-P** IRIS-Pacific - NAO Mizusawa (in beginning probably still IPMS)
- **IRIS-S** IRIS-South - Geodetic Institute, Bonn + IfAG + Wettzell
- **MOBL** mobile VLBI in N. America - NASA
- **NAVEX** USNO - extended networks
- **NAVNET** USNO - EOP monitoring
- **NEOS-A** National Earth Orientation Service (USNO, NOAA, NASA) - EOP monitoring
- **NEOS-B** EOP monitoring - different network than NEOS-A
- **NGS** NGS sessions in southern hemisphere and Canada
- **NRL** Naval Research Laboratory - astrometry
- **POLA** POLARIS - NOAA (in those days actually NGS, a small part of NOAA)
- **SGP** Space Geodesy Program - NASA (name created by Goddard)
- **USNO** early EOP's
- **VLBA** Very Long Baseline Array
BIBLIOGRAPHIC REFERENCES TO VLBI CELESTIAL REFERENCE FRAME WORK


