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The Essential Contribution of VLBI to Fundamental Astronomy

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Abstract

The adoption of the International Celestial Reference System ICRS based on VLBI observations of extragalactic radiosources, by the International Astronomical Union (IAU), since 1st January 1998, has open a new era for astronomy. The ICRS and the corresponding frame ICRF replaced the FK5 based on positions and proper motions of bright stars. According to its definition, the ICRS is such that the barycentric directions of distant extragalactic objects show no global rotation with respect to these objects. The old dream of astronomers of an absolute reference for measuring the angular motion of celestial bodies has thus become reality. This results in an historical abandonment of the link of the celestial reference system with the motion of the Earth. This has to be taken into account by revising the current concepts of fundamental astronomy; IAU 2000 Resolutions provided new definitions for the celestial pole, Universal Time and parameters to be used in the transformation between celestial and terrestrial frames, in consistency with the properties of the ICRS. VLBI observations of Earth orientation referred to the ICRS provide very accurate determination of the actual celestial position of the pole and of the Earth's angle of rotation. This has led to significant improvements in the models for variations of Earth's angular velocity as well as for precession and nutation. Such models are very useful for astrometry and provide a better knowledge of the dynamics of the Earth's interior.

1. Introduction

Fundamental astronomy is concerned by the determination of positions and motions of celestial objects. Therefore, it requires definition and realization of reference systems, maintenance of the reference frames which realise the systems, improvement of the models for the observables, and determination of Earth orientation on a regular basis.

This paper emphasizes the essential contribution of VLBI for defining and realizing the fundamental quasi-inertial celestial reference system, for making possible the definition of more basic concepts in fundamental astronomy and for providing accurate Earth orientation parameters.

2. Essential Contribution of VLBI for the Celestial Reference System

2.1. The Availability of an Absolute Celestial Reference System

The availability of an absolute reference system is required for celestial dynamics. A catalogue of stars, even it is constructed in order to realize a dynamical reference system, as is the FK5 [11], cannot be realized without any rotation, due to the inaccuracies in the estimation of proper motions of stars. This is actually a critical problem and only extragalactic objects, which do not participate in the rotation of the Galaxy, can provide convenient fiducial points. This had already been discussed by Hershel [14] as well as by Laplace [16] in the 18th century, but extragalactic objects have only been discovered in 20th century and compact radio sources as quasars in the 1960s. The hypothesis that the Universe as a whole does not rotate is necessary and seems to be confirmed by observations. VLBI is, at present, the only technique which can provide the measurement of the directions of quasars with a sufficient accuracy such that it is the unique technique which can realize an absolute celestial reference system.

These issues have been largely discussed by Ma [18], [19] and by Walter & Sovers [31].

2.2. The IAU Fundamental Celestial Reference System

The FK5 (Fundamental catalogue) ([11] [12]) has been the IAU celestial reference system from 1976 to 1997. It was based on a concept of dynamical reference system in order to be an "absolute system" and it was realized by positions and proper motions of nearby bright stars. It was oriented so that at a given date, the positions are referred to the best estimate of the location of the mean pole and mean equinox of epoch. The proper motions were evaluated so that, for a given model of precession, they provide the best access to the mean pole and mean equinox of epoch (J2000) at any other date. Its precision is of the order of 0.02" for positions and 1 mas/c for proper motions (see Table 1). The so-called "FK5 System" refers to the FK5 catalogue and to the associated IAU 1976 model for precession [17], the IAU 1980 theory of nutation [27] and GMST/UT1 relationship [1]. Since 1988, there have been successive IAU Resolutions for the adoption of a new celestial reference system based on extragalactic radiosources :

- the IAU General Assembly in 1988 called for the use of extragalactic objects to define the celestial reference frame,
- the IAU GA 1991 adopted General Relativity as the fundamental theory, confirmed 1988 Resolution and specified the continuity with existing stellar and dynamic realisations,
- the IAU GA 1994 adopted a list of some 600 extragalactic radio sources and formed a Working group to define the positions,
- the IAU GA 1997 resolves : (a) that, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on reference frames and as defined by the International Earth Rotation Service (IERS) [2] ; (IERS Technical Note 1997), (b) that the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames [18],
- the IAU GA 2000 provides a clarification of IAU's 1991 definition of the coordinate systems in the framework of General Relativity, making a distinction between the system of space-time coordinates (a) for Solar System (BCRS) which can be considered to be a "global coordinate system" that contain all the "far away regions" [28] and (b) for the Earth (GCRS) which can only be considered as a "local coordinate system".

2.3. The Significant Change from FK5 to ICRF

The International Celestial Reference System ICRS adopted by the IAU to replace the FK5 since the 1st January 1998 as the fundamental celestial reference system is such that the barycentric directions of distant extragalactic objects show no global rotation with respect to these objects. It was specified that the orientation of the GCRS follows the kinematical condition of absence of global rotation of geocentric directions w.r.t. the objects defining the ICRS [2]. The maintenance of the axes is obtained by a statistical condition that the coordinates of selected "defining sources" (see Figure 1) show no global rotation when improving positions. The ICRF [20] was aligned with the FK5 at J2000 but no attempt is made to refer the positions of the sources to the mean pole and mean equinox at J2000. It is no longer dependent on the Earth's motion and further improvement of the ICRF will be accomplished without introducing any global rotation. The ICRF is therefore independent from precession-nutation models. This actually corresponds to an historical abandonment of the link of the celestial reference system with the motion of the Earth.

2.4. The Fundamental Role of VLBI and IVS for the ICRF

In 2000, the IAU adopted the Resolution B1.1 untitled "Maintenance and establishment of Reference frames and Systems" which recognizes :

1. the importance of continuing operational observations made with VLBI to maintain the ICRF,
2. the importance of VLBI observations to the operational determination of the parameters needed to specify the time-variable transformation between the International Celestial and Terrestrial Reference Frames.

The IAU 2000 Resolution B1.1 also recommends the following role for IVS :

1. that IAU Division I maintain the WG on Celestial Reference Systems formed from Division I members to consult with the IERS regarding the maintenance of the ICRS,
2. that the IAU recognise the International VLBI Service (IVS) for Geodesy and Astrometry as an IAU Service Organization,
3. that an official representative of the IVS be invited to participate in the IAU Working Group on Celestial Reference Systems,
4. that the IAU continue to provide an official representative to the IVS Directing Board.

2.5. The International Reference Frame, ICRF and its Extension

The ICRF has been provided by the IAU WG which was formed in 1994. It is realized [21] by the coordinates of 608 extragalactic radiosources with an accuracy from 0.4 mas to 1 mas (see Table 1 and Figure 1). These sources are divided in three categories according to quality criteria. It includes 212 defining sources, corresponding to the best observed set of sources, 294 candidate sources and 102 others sources; the stability of the axes is ensured by the defining sources at the 20 microarsecond level. The coordinates of the sources result from the analysis of 1.6 million observations of dual frequency delays and rates during the period 1979-1995.5 using 24-hr VLBI sessions. The abandonment of the link of the CRS with the motion of the Earth requires that an offset at epoch be introduced in the description of the precession-nutation of the Earth's pole, this offset being experimentally determined and being revisable in conventionally adopted models of precession-nutation.

The maintenance and extension of the ICRF, which is one of the tasks of the IAU Working Group ICRS with IERS and IVS, is based on geodetic and astrometric observing VLBI and VLBA programs such as CORE, NEOS, RDV (VLBA). The ICRF-Ext.1 is the first extension of the ICRF [20] adding 59 new sources (see Figure 2) and improving positions and errors for the candidate sources, but with unchanged positions and errors for the defining sources in order to realize the ICRF as defined previously. It results from the re-analyzing of the 1979-1999 data set adding 600,000 observations in 461 sessions and refining the analysis. Further extensions of the ICRF would represent a valuable contribution to fundamental astronomy.

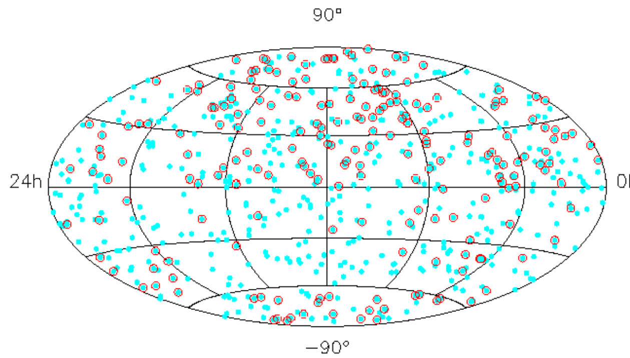

Figure 1. The catalogue ICRF (Ma *et al.* 1998), defining sources: filled circles.

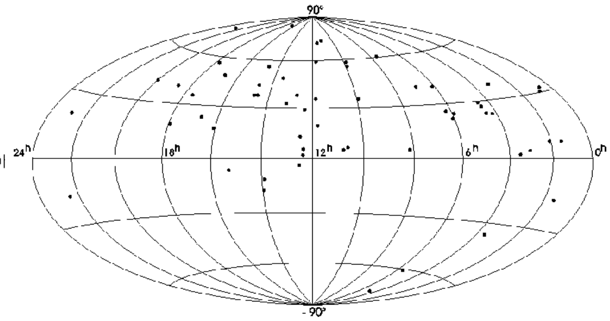

Figure 2. The ICRF-Ext1 catalogue (IERS 1999, Ma 2000).

2.6. The ICRS as the Primary Reference System for Astrometry

The ICRS, as the fundamental celestial reference system, constitutes the primary reference system for astrometry to which all global catalogues and surveys have to be tied. The FK5 has been tied to the ICRF [23] and Hipparcos Catalogue (ESA 1997) was adopted by the IAU in 1997 as the optical realisation of the ICRS. It had been tied to ICRF with a positional accuracy of 0.60 mas at 1991.25 ± 0.25 mas /yr [15]. Such a realization through the 100,000 good sources of the observed stars of the Hipparcos mission has been labelled HCRF for "Hipparcos Celestial Frame". At the mean epoch, 1991.25, of the space mission, the positional accuracy is of the order of 1 mas, but this accuracy degrades quickly with time (see Table 1) due to the inaccuracies in proper motions of stars. HCRF also suffers from a too low density on the sky as well as to the fact that the core of the HCRF is made of sources usually too bright to be used as reference stars for high accurate astrometric measurements of faint celestial objects [24].

The densification of the HCRF, the optical counterpart of the ICRF, as well as the extension of the ICRF in other wavelengths are major tasks of the IAU Working Group ICRS with IERS and IVS. First densifications in the optical wavelengths have already been achieved (e.g. Tycho-1, ACT, TRC, Tycho-2) and other are under realization (e.g. US Naval CCD Astrograph Catalogue) and IR surveys such as 2MASS and DENIS will lead to an extension of the ICRF in the near IR. The future space astrometric missions such as DIVA, FAME, SIM and GAIA will open new perspectives within the next twenty years.

2.7. The ICRF as the Primary Reference Frame for Celestial Dynamics

Until recent years, celestial dynamics referred to various "dynamical" celestial reference systems which were linked together in a very complex way [10], [8].

New ephemerides in the Solar System now refer to the ICRS. Recent numerical JPL ephemerides DE405 and LE405 have been referred to the ICRF using adjustements to VLBI observations of spacecraft around Venus and Mars, providing the orientation w.r.t. IRCS with an accuracy of the order of 1 mas [30]. Recent analytical ephemerides of the planets [25] or the Moon [8] also referred to the ICRF, which has now become the primary reference systems for celestial dynamics.

In addition, the orientation of the equator and ecliptic have been recently referred to the ICRF at a submilliarsecond accuracy thanks to the joint use of lunar laser ranging and VLBI observations for the location of the dynamical ecliptic in the ICRF [8] and thanks to VLBI observations for the position of the mean pole at J2000 in the ICRF [21].

It has to be noticed that such an evolution of the celestial reference frames from a dynamical concept to a "natural" concept is very similar to the evolution of the reference time scales during the 20th century from the concept of Universal Time as realized by Earth rotation, to the International Atomic Time, TAI [5] (see Table 2).

Table 1. Evolution of celestial reference frames

Name	Fiducial objects	Number	Limit of magnitude	Mean time of observations	Observation Technique	Uncertainties: pos., proper motion	Status
FK5	stars	1535 3117	< 7 < 9.5	1940 - 1950	Optical astrometry	0.02" 0.0008"/y 0.08" 0.002 "/y	Fundamental catalog from 1976 to 1997
ICRF	Extra galactic radiosources	212 defining 398 others		1987	VLBI	0.0004" 0.001"	Celestial reference frame from 1998
Hipparcos catalogue	stars	118 218	< 12	1991.25	Astrometric satellite Hipparcos	10^{-3}" 10^{-3}"/y	HCRF: Optical counterpart of ICRF

Table 2. Evolution of reference time scales

Time scale	Physical phenomenon	Irregularity	Uncertainty of reading	Use for celestial dynamics
Universal time (UT1)	Earth rotation	10^{-7}	5.10^{-5} s	Until 1950
Ephemeris time (ET)	Earth orbital motion	10^{-9}	0.1 s	Until 1995
Internat. atomic time (TAI)	Hyperfine atomic transition	10^{-14}	5.10^{-9} s	Since 1955

3. Essential Contribution of VLBI for Concepts in Fundamental Astronomy

3.1. Improvement in the Concepts of Earth's Orientation

The new concept of the celestial reference system based on a kinematical definition of no global rotation, on which relies the definition of ICRS, must be associated with the revision and the improvement of concepts regarding the Earth's orientation in space. This is necessary in order that the stability of the ICRS is maintained and that the accuracy of the estimated parameters to which VLBI is sensitive is not perturbed. Actual pole and UT1 are estimated by VLBI in the ICRF through a very simple geometric principle which has not to be damaged by the use of old and complicated concepts which are no more adequate [4]. Concerning the classical reference to the equinox, which is the intersection between the ecliptic and the equator, it is important to note that VLBI observations of quasars are not sensitive to its position and that moreover, in General Relativity, the ecliptic is a BCRS coordinate object related with the Earth's ephemerides, whereas the equator is defined in the GCRS only [28].

The relationship between GST and UT1, referring to the equinox, contains the accumulated precession and nutation in right ascension as well as the accumulated coupling between precession and nutation [7]. New parameters are therefore necessary to replace the classical parameters for precession [17], nutation [27] and sidereal angle [1], which are referred to the FK5 (i.e. to the ecliptic and the equinox, see Figure 3). A new definition of the pole is also required to be in agreement with the submilliarsecond accuracy as provided by VLBI estimation of the celestial pole offsets.

Several resolutions were adopted by the IAU in 2000 regarding transformation between the celestial and terrestrial reference systems to be implemented in the IERS procedures beginning on 1 January 2003.

Resolution B1.7 recommends that the Celestial Intermediate Pole (CIP) be implemented in place of the Celestial Ephemeris Pole (CEP) in order to extend the definition in the high frequency domain and coincides with that of the CEP in the low frequency domain [5].

Resolution B1.8 recognizes the need for a rigorous definition of sidereal rotation of the Earth and the desirability of describing the rotation of the Earth independently from its orbital motion and therefore recommends the use of the "non-rotating origin" [13] both in the GCRS and the ITRS. These origins are designated as the Celestial Ephemeris Origin (CEO) and the Terrestrial Ephemeris Origin (TEO). The "Earth Rotation Angle" is defined as the angle measured along the equator of the CIP between the CEO and the TEO. This Resolution recommends that UT1 be linearly proportional to the Earth Rotation Angle and that the transformation between the ITRS and GCRS be specified by the position of the CIP in the GCRS, the position the CIP in the ITRS, and the Earth Rotation Angle [6].

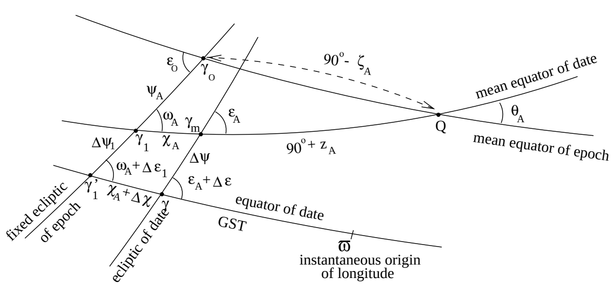

Figure 3. Earth orientation parameters (precession, nutation, GST) in the FK5

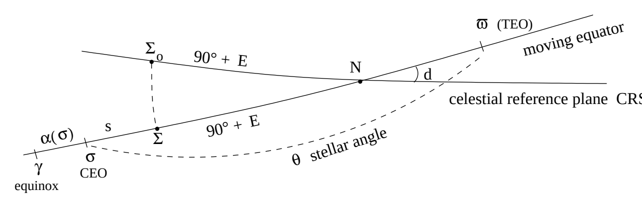

Figure 4. Earth orientation parameters (E, d, θ) referred to the ICRS

3.2. The Earth Orientation Parameters Referred to the ICRS

The new concepts for the EOP referred to the ICRS, as adopted by the IAU in consistency with the ICRS, are such that they abandon the current parameters in the FK5 System and they abandon the current formulation which combines the motions of the equator and the ecliptic w.r.t. the ICRS. The Earth's angle of rotation is no more reckoned from the true equinox in order to clearly separate precession-nutation from Earth rotation and to include both precession and nutation in the new parameters X and Y. It must be noticed that the new adopted reference for UT1, the NRO [13], is actually an unavoidable origin to express a rotation along the moving equator.

The new parameters as adopted by the IAU allow the parameters to clearly separate high frequency and low frequency motions. This reduces to five the parameters for transformation between ITRF and GCRF [3]: two (E, d) for the position of the CIP in the GCRS, two (F, g) for the position of the CIP in the ITRS and one for the Earth's angle of rotation; this provides a symmetric representation for the celestial and terrestrial parts of the motion : $PN(t) = R3(-E).R2(d).R3(E)$ for precession-nutation and $W(t) = R3(-F).R2(g).R3(F)$ for polar motion.

The position of the CEO in the GCRS is given by the quantity s, which can be expressed by a development as function of time [6]. The relationship between the Earth's rotation angle and UT1 is linear [6] and ensures the continuity in phase and rate of UT1 with the value obtained by the conventional relationship between Greenwich Mean Sidereal Time (GMST) and UT1 [1]. Such a linearity represents a significant improvement in the defintion of UT1.

4. Essential Contribution of VLBI for Earth Orientation

4.1. The Accurate Determination of UT1

Improvement in precision and time resolution of the estimation of UT1 has been from 1 mas with a resolution of one day in 1980 to 0.1 mas with a resolution to one hour in 2002. There have been, moreover, improvement in strategy and procedures and the combined use of several high precision techniques (VLBI, GPS, ...).

Among these techniques, VLBI is the only one which provides the determination of the actual angle of Earth's rotation in the GCRF (see Figure 5) as well as of the actual position of the pole at the date of the observation in the GCRF (see Figure 6). This is of major importance for the knowledge of the variations in length of day (l.o.d.) which include variations from secular to sub-daily periods.

The determination of UT1 by VLBI provides the reference of this angle for all other techniques (GPS, SLR, LLR,...), with an accuracy of 5 μs for UT1 as estimated during 1d-session and 20 μs for UT1 estimated for 1h intensive sessions [26].

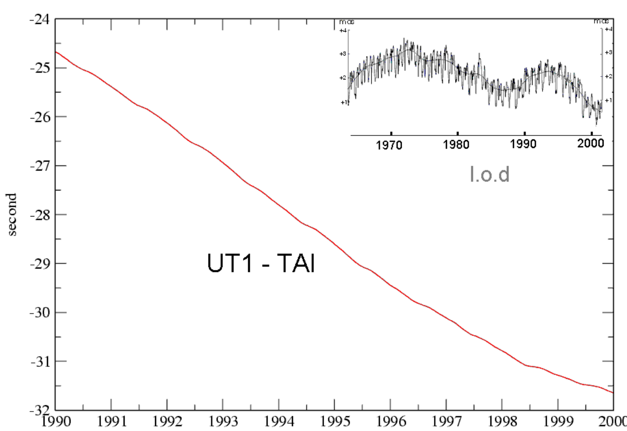

Figure 5. Estimation of UT1-TAI from VLBI (GSFC)observations from 1990 to 2000

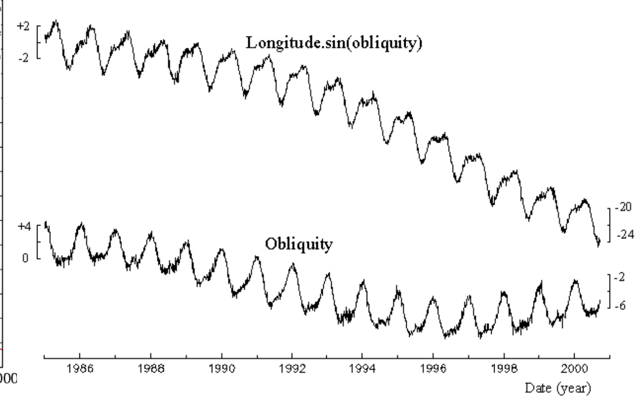

Figure 6. Celestial pole offsets estimated from VLBI observations (1982-2001).

4.2. The Accurate Determination of Precession and Nutation

Large improvements have been obtained recently in the nutation theory as well as in the estimation of the precession-nutation motion from VLBI observations [9]. Resolution B1.6 of the 2000 IAU GA recommended that the IAU 1976 precession model [17] and IAU 1980 theory of nutation [27] are replaced by the IAU 2000 precession-nutation model. This model is based on a new rigid Earth nutation model [29] and a new transfer function of Mathews *et al.* [22] whose coefficients are adjusted on VLBI observations.

The IAU 2000A (for 0.2 mas level) and IAU 2000B (its shorter version, for 1 mas level) with the associated precession and obliquity rates and celestial pole offsets at J2000 adjusted on VLBI observations, will replace the previous IAU models beginning on 1 January 2003.

The transfer function from the rigid to the non-rigid Earth model is based on improved geophysical parameters estimated from VLBI (see Table 3) and improved precession rates in longitude and obliquity. Due to the definition of the CIP, the prograde diurnal and semi-diurnal terms in nutation (with amplitudes of the order of 15 microarseconds) are considered as variations of polar motion [4]. Comparisons of the models with VLBI observations show an agreement of the order of 200 microarseconds [9].

Table 3. Estimates of Basic Earth Parameters from least squares fit by Mathews *et al.* (2001)

Basic Earth Parameters	Estimate	Adjustment
e_f	0.0026456 ± 20	0.0000973
κ	0.0010340 ± 92	- 0.0000043
γ	0.0019662 ± 14	0.0000007
e	0.0032845479 ± 12	0.000037
Im $K^{(CMB)}$	-0.0000185 ± 14	..
Re $K^{(ICB)}$	0.00111 ± 10	..
Im $K(^{ICB)}$	-0.00078 ± 13	..
rms $(sd)_{input}$	0.0039	..
rms residuals	0.0132	..

Improvement in the model for nutation corresponds to a better knowledge of the dynamics of the Earth's interior. One illustration is the period of the Free Core nutation (FCN) [22], which is closely linked to the dynamical flattening of the outer core, e_f (see Table 3). Geophysical model PREM gives a perid of 458 days, whereas VLBI estimate is 430.20 ± 0.28 d (see Figure 8) which corresponds to a difference of 350 m in e_f resulting from the non-hydrostatic effect plus electromagnetic coupling.

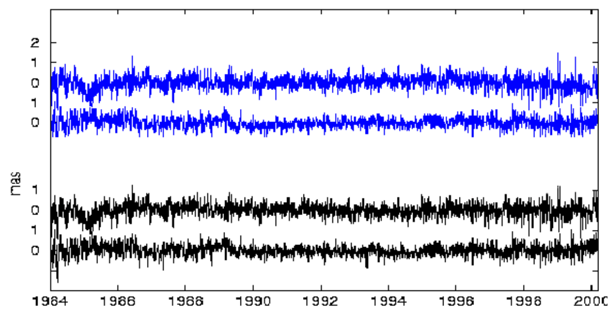

Figure 7. Comparison between models (top: MHB2000, bottom: IERS1996) and VLBI observations (from Dehant *et al.* 1999).

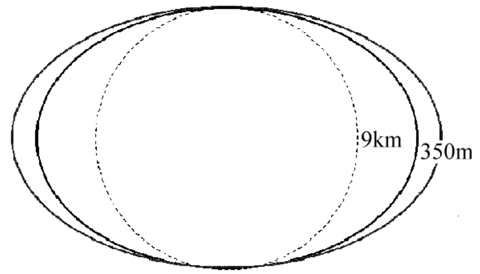

Figure 8. Comparison between the geophysical model (PREM) and VLBI estimate of the fluid core flattening (from Dehant *et al.* 1999).

5. Conclusion

Thanks to VLBI, a new celestial reference system is available based on directions of extragalactic radiosources. This new system, ICRS, which is a quasi-inertial system, opens a new era in astronomy. Positions and proper motions of stars are now expressed in the corresponding frame, the ICRF, as well as positions of celestial objects observed at other wavelengths and solar system ephemerides. Earth rotation being observed with respect to the ICRS, the concepts regarding this motion will benefit from its property which leads to a potential improvement in accuracy of the EOP.

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