Applications of VLBI to Geodesy *

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Abstract

Although Very Long Baseline Interferomentry (VLBI) is a observation technique of radio astronomy, it is used in geodesy for about two decades. It is one of the space techniques which allows precise measurement across the oceans. Today VLBI is an established measuring technique which provides unique results in monitoring Earth orientation and it became the primary technique to tie terrestrial reference systems to the celestial reference system. The geodetic VLBI programs provided most of the data for the radio source based celestial reference system. VLBI is still used in geodynamic investigation to improve plate tectonic models. Astrometry controls the evolution of the radio sources. Todays geodesy is without VLBI unthinkable.

1 Geodesy and VLBI

Geodesy is the science of determining the size and the figure of the Earth and its external gravity field [19].

Geodesists need *reference systems* in order to describe the topography of the Earth with coordinates. Those *coordinates* (see [7]) are necessary for many applications as such as mapping, land register, navigation, constructions, etc..

In 1979 NASA started the "Crustal Dynamic Project" to improve the understanding of geodynamic processes. The objectives required the development of global geodetic measuring systems, that could measure distances with high accuracy [16]. As a result the geodetic VLBI system Mk3 and instrumentations for another complementary technique Satellite Laser Ranging (SLR) were developed. During the first years of CDP the VLBI and the SLR techniques had served as the backbone tools of the CDP. During the late 80-ties another revolutionary geodetic space technique was started to be employed: the Global Positioning System (GPS).

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Nearly two decades of using all three geodetic space techniques VLBI, SLR, GPS almost independently of each other calls for a validation of each individual technique [2]. For understanding the application of VLBI to geodesy in the present a few remarks on *reference systems*, *geodynamics*, *astrometry* appear to be necessary.

2 Reference Systems and Earth Orientation

In general reference systems are used for the coordination of events. The coordinating event and the carrier of the reference system are tied by signals. Of course the carrier of the reference system has to be cooperative with respect to the measuring device.

The carrier of reference systems are usually objects, which allow marking at particles of matter. Therefore quasars, stars, satellites and ground markers allow the fixation of reference systems. The relations of the markers to each other are describing physical abilities of the carrier, which are e.g. proper motions of stars and/or stations, orbit elements of satellites.

In the *theory of systems* one distinguishes between a global system, which has only neglectable interdependencies with its environment and an arbitrary limited system which interacts with its environment. Usually the arbitrary system can be interpreted as a subsystem to a global system.
The high level of accuracy in todays geodetic space techniques let the system Earth appear as a subsystem to the solar system and contains itself subsystems of the geo-, bio-, and anthroposphere. Applied to geodetic reference systems it is important to *tie* the sub-reference-systems to a global-reference-system.

Two distinct reference systems are to be noted:

- space fixed non-rotating reference systems; e.g. celestial frames,
- earth fixed rotating reference systems; e.g. terrestrial frames[1].

Fig. 2 explains the link between an extraterrestrial and terrestrial reference system. The key for accurate transformations is the precise determination of the Earth orientational parameters (EOP[2]) for precession, nutation, polar motion and $UT1 - UTC$. The orientation of reference systems is preferably realized by using natural directions like “fix”-stars (stellar compass, [20]) or Earth's rotational axis (inertial compass, [17]) or the vertical due to gravitation (gravitational compass).

Among the different geodetic space techniques VLBI provides the most accurate Earth orientation parameters. In addition it is known, that EOP derived from satellite methods tend to drift without EOP determined by VLBI.

Tab. 2 [2] shows, that

[1]A reference *system* is made by definition, while a reference *frame* is any representation of the definition based on a set of observations.

[2]From the mathematical point of view just three parameter would be sufficient for the description of the Earth rotation. But there are two reasons two use the historical five parameters: 1. the periods are very different, 2. precession and nutation are caused by extraterrestrial bodies, polar motion is caused by mass movements in the interior, $UT1 - UTC$ reflects many causes.

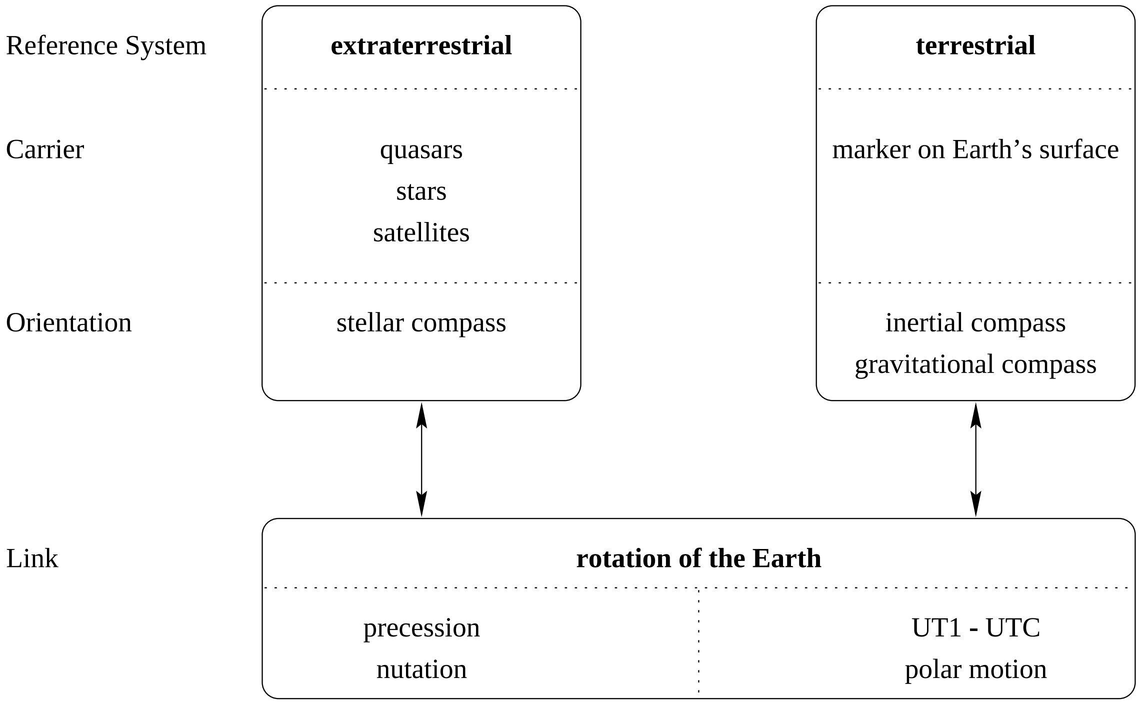

Figure 1: Link between two reference systems by rotational components of the Earth.

- VLBI determines independently all five EOP at once,
- VLBI is the unique geodetic space technique for the determination of the nutational parameters, which are necessary for the establishment of a celestial reference frame and the improvement of the nutation model,
- VLBI is more accurate.

All satellite based techniques determine the EOP relative to the orbiting satellites. The orbit is subject to pertubations by the irregular gravitational field of the Earth and from other bodies like the Sun and the Moon and also to non-gravitational accelerations from sources as spacecraft outgassing and atmospheric drag. Therefore the satellite methods cannot separate variations in orbital elements from changes in the orientation of the Earth without additional informations(!), as they are provided by VLBI [5]. However VLBI by its kinematic character cannot contribute to the determination of the center of mass of the Earth, which is preferably use as the origin of geocentric reference systems. In this case satellite techniques are a necessary complement to VLBI.

2.1 Earth Orientation Parameter Determination

Since the EOP are essential to understand the system Earth the previous EOP monitoring programs like IRIS/NEOS are being replaced by the "Continous Observations of the Rotation of the Earth" program (CORE). In different day-by-day networks a continous

Analysis Center	Technique	Uncertainty of EOP Determination X [mas]	Y [mas]	UT1 [0.1ms]	$d\psi$ [mas]	$d\epsilon$ [mas]
GSFC	VLBI	0.32	0.27	0.09	0.10	0.08
NOAA	VLBI	0.24	0.30	0.10	0.25	0.10
USNO	VLBI	0.20	0.16	0.10	0.19	0.08
CSR	SLR	0.20	0.22	0.51	-	-
CODE	GPS	0.33	0.36	0.45	-	-
EMR	GPS	0.35	0.35	0.45	-	-
GFZ	GPS	0.35	0.26		-	-
JPL	GPS	0.34	0.34		-	-

Table 1: Uncertainties of EOP Determination (1993-1994) based on Allan Variance Analysis of the Difference between Series. VLBI is superior.

VLBI operation is envisaged. The deployment of Mk4 VLBI technology with increased sensitivity promises a significant contribution to Earth system science (see Fig. 2.1, 2.1 from [4]). Models for Earth core modes and libration will become necessary.

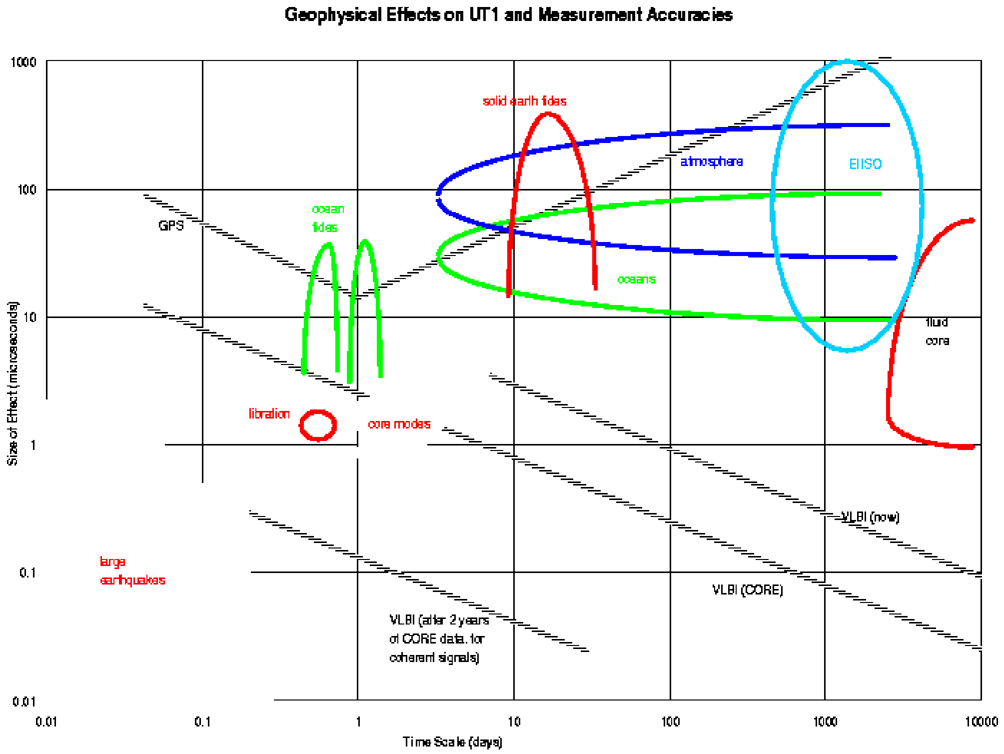

Figure 2: Proposed increase of accuracy in the determination of UT1.

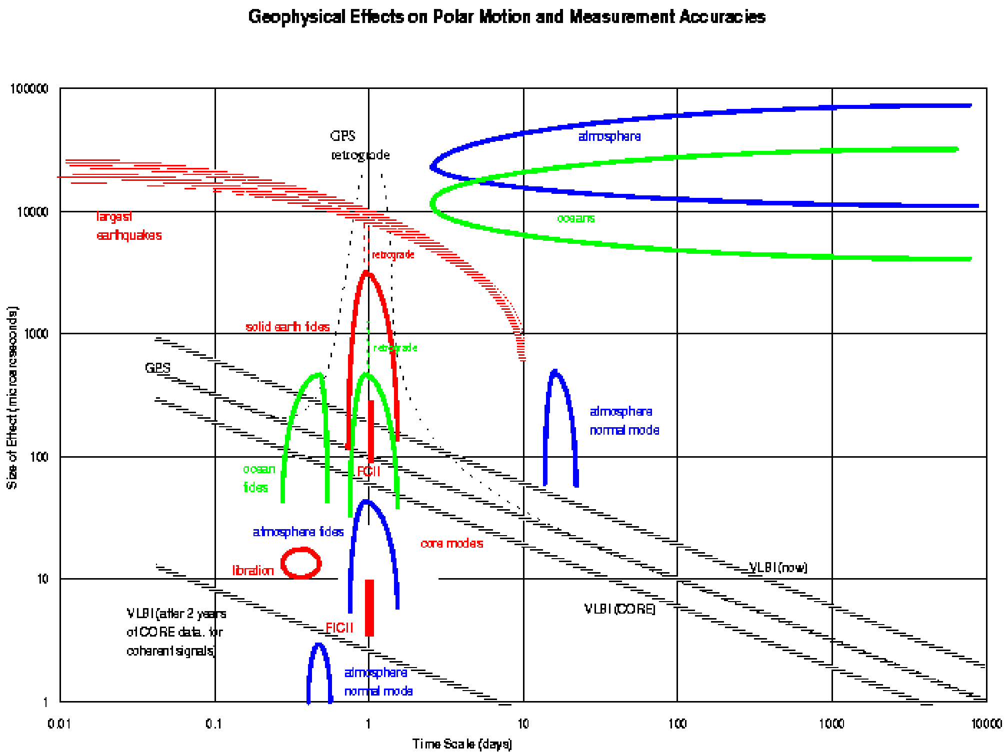

Figure 3: Geophysical effects on polar motion and the measurement accuracies.

2.2 Celestial Reference Frame

The description of the location of the Earth in the universe which is necessary for all space related activities including (radio) astronomy requires a celestial reference system. Among different international recognized reference frames the important are in

1. optical astronomy
   - Fifth Catalog of Fundamental Stars (FK5) [6],
   - Hipparcos catalog,
2. radio astronomy
   - IERS Celestial Reference Frame [1],
   - USNO Radio Reference Frame [10].

As an example the latter one will be discussed. The reference frame is based on VLBI observations of 560 sources in S/X-band covering a period from the end of 1979 until the beginning of 1994.

Total number of VLBI-observations	1.015.292
Earth rotation VLBI-observations	$\approx$ 570.000
geodynamic VLBI-observations	$\approx$ 380.000
astrometric VLBI-observations	$\approx$ 34.000
source determination VLBI-observations	$\approx$ 23.000

Table 2: Quantitative contributions to the USNO radio reference frame. The determination of one groupdelay from the signal of one source on one interferometer baseline is called one VLBI-observation. The scientific aims of the majority of the contributors were not initially to determine a good celestial frame!

Tab. 2.2 demonstrates that data from geodetic VLBI experiments for monitoring Earth rotation and geodynamics could be used as the backbone for the determination of celestial reference frame. The accuracy of the sources depend on the number of observations, of the source structures and of proper motion. Johnson et al. introduced a classification of sources due to their accuracies, see Tab. 2.2.

Class	Property	Number
1	$< 1mas$ formal accuracy, > 50 observations	N:163, S: 48
2	$< 3mas$ formal accuracy, > 10 observations	N: 98, S:127
3	$> 3mas$ formal accuracy, < 10 observations	46
4	galactic or nearby-extragalactic, proper motions	5
5	strong source structure, position dependent of station network	20
6	bad/no data, excluded from solution	53

Table 3: Source classification in the USNO Radio Reference Frame. The relation of class 1 and class 2 sources between north- and southern hemisphere is 261:175.

Tab. 2.2 also indicates the inbalanced distribution of high quality sources between northern and southern hemisphere (Fig. 2.2). More southern observatories are desirable in order to get more data on southern hemisphere sources.

It is known, that the center of a source might be different at other wavelengths than those of S/X-band. But at other wavelengths there are only a fraction of VLBI observations available, which cannot provide the accuracies on the $1 - 3mas$-level.

An interesting geodetic task is also to link reference frames of different wavelengths. This is possible only with identical objects either at the sky or at the site.

3 Geodynamics

VLBI has the capability to determine terrestrial distances up to $10.000km$ on the accuracy level of a few millimeters. It is important for the maintenance of terrestrial reference frames based on that accuracy to take the geodynamic phenomenas into account.

In order to achieve comparable results from the global analysis of geodetic space techniques the International Earth Rotation Service (IERS) issued a standard [13] for the consistent modelling of geodynamic phenomena.

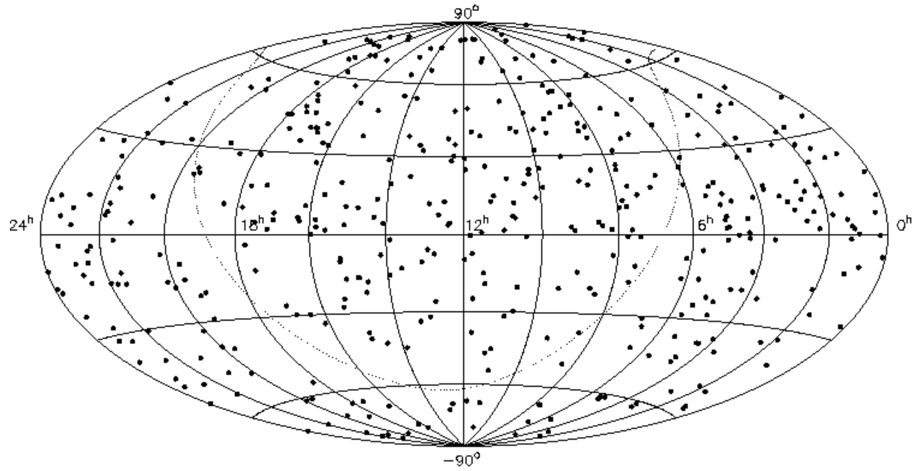

Figure 4: The distribution of radio sources of the USNO Radio Reference Frame. The dotted line indicates the ecliptic.

These effects demonstrate that the Earth is not rigid. The accuracy of geodetic space techniques require the modelling of the geodynamic phenomena in order to avoid systematic errors by the interpretation of (VLBI) baseline results. Models are continously validated and improved as soon as new systematics can be identified.

The baseline Wettzell-Westford shows, that in the early 80-ties the models have not been as accurate as in the late 80-ties. Also it can be seen, that with the decrease of errors, new seasonal variations occure. Above all is the continental drift between North-America and Eurasia significant.

Baselineplots like Fig. 3 can be compared with the plate motion model NUVEL-NNR1A which is derived from geophysical information like magnetic anomalies at midocean ridges, azimuths of transform faults and earthquake slip vectors at plate boundaries with respect to geological informations. It covers the past 25 million years of motion of the plates [18]. In contrast the modern space geodetic techniques like VLBI can provide data about plate motion of one and a half decade. It is interesting, that the NUVEL-NNR1A model can be confirmed for many regions. Fig. 6[3] shows the residuals between NUVEL-NNR1A and the geodetic VLBI estimates. Thanks to model improvement and the increasing global coverage with space geodetic site which perform permanent observation it might be possible to predict earthquakes in the future.

A new interpretation of VLBI for plate tectonics is being carried out within the Japanese Key Stone Project. Four radiotelescopes in the metropolitan area of Tokyo form a real-time

[3]"This research has made use of NASA Goddard Space Flight Center's VLBI terrestrial reference frame solution number 1083c, 1997 August."

Geodynamic Phenomena		
Type	IERS-Convention	Reference
Precession	IAU 1976 Precession	IAU recommendation 1976, 1979
Nutation	IAU 1980 Theory of Nutation	Seidelmann, 1982; Wahr, 1981
Plate Motion	NNR-NUVEL1A	DeMets et al., 1994
Geopotential (Tides)	JGM-3	Tapley et al., 1995
Ocean Loading	IERS Conventions, 1996	
Solid Earth Tides	IERS Conventions, 1996	
Rotational Deformation due to Polar Motion	IERS Conventions, 1996	
Antenna Deformation	IERS Conventions, 1996	
Atmospheric Loading	IERS Conventions, 1996	
Postglacial Rebound	ICE-4G	Peltier, 1994
UT1 Variation	Tidal Variations in Earth's Rotation	Ray et al., 1994
Troposhere	Mapping functions for delay	IERS Conventions, 1996
General Relativity	Consensus Model	Eubanks,1991

VLBI array for monitoring the crustal deformation in the collision zone of the eurasian, north-american and phillipine plate [11].

4 Astrometry

The radio sources are the natural targets in geodetic VLBI. Monitoring the Earth related parameters like orientation, tides, geodynamics on a long time scale, we need to "calibrate" our targets periodically. Astrometry is the positional astronomy which tells us whether the source is point like or has structures and where the center of a radio source is. Even if radio sources used by geodetic VLBI are supposed to be stable and point like, it is necessary to do astrometry with them. Hereby it is an advantage that geodetic VLBI experiments are carried out frequently, which gives a large set of data at many epochs.

Britzen [3] was analyzing the structure of the source 1803+784 during a period from 1986.21 until 1992.34 using 42 geodetic VLBI-experiments (see Fig. 4 shows, that the source contains moving, oscillating and stationary components.

5 Technical Aspects in Geodetic VLBI

What makes geodetic VLBI different from VLBI for radio astronomy? Most of the differences are obvious, if one notices that the group time delay is the primary observable.

1. *Dual-band observations* in S- and X-band enables a compensation for the transmission delay in the ionosphere.

2. *Phasedelay calibration system* enables the introduction of relative delay variation in the IF-cables due to gradients in the ambient temperature.

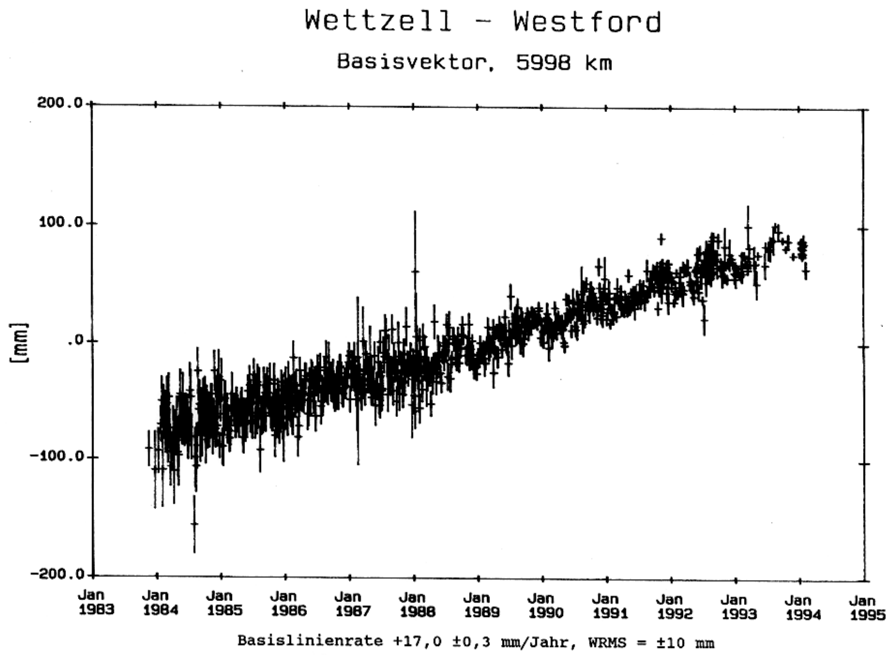

Figure 5: The very frequent observed baseline Wettzell-Westford. Formal errors have been much higher in the beginning, when models weren't so elaborated. New seasonal systematics appear when models remove noise.

3. *Monument/telescope stability* needs to be controlled periodically by local surveys to be sure on continental drifts rather than local tectonic effects.

4. *Schedules* try to observe as many sources per time as possible and also at low elevations in order to achieve a good geometrical stability for site coordinate determinations. Experiments have usually a duration of $24h$ to cover a full period of daily phenomenas.

5. *Sources* are ideally point-like and with neglectable proper motion.

6. *Observational programs* need to be oriented to geological time scales and will get (hopefully) a long-term history.

6 Outlook

Even if geodetic VLBI is a well established technique, there exist still challenging scientific task to resolve. It is known, that the technology provides an accuracy of millimeter-level while the current modelling is accurate on the centimeter-level only.

One of the most degrading effects especially for the vertical component is the modelling of the signal transmission in the troposphere. The exisiting models are either dependent on meteorological surface measurements (Lanyi [12], Ifadis [9], Herring [8]) or on the

conditions in the atmosphere approximately $1km$ above ground (Niell, [14]).
Another approach is the "Differential-VLBI" which will allow phasedelay measurements.

Another problem is the insufficient modelling of nutation. The suggested IAU model 1980 needs to be replaced by a new one based on VLBI-data, which provides a higher resolution.

The third problem is the correct modelling of rotation in general relativity. At present the VLBI analysis software uses "correction terms" for delays due to gravitation. If rotation in general relativity can be modelled a new 4-dimensional VLBI model in spacetime will become available [15].

7 Conclusion

Geodetic VLBI will exist in the future, since it is the only space technique which provide a link to the celestial reference system on the highest level of accuracy. The precise knowledge of actual Earth orientation parameters is vital for all space navigation purposes and has in impact of any space project. Therefore geodetic VLBI will continue to produce regular high quality data in the next future with a global network of about 20-30 VLBI-Mk4 stations.

Although the geodetic VLBI is attached to the "most boring" sources, it is the hope of the author, that geodetic VLBI-data will find the interest of radio astronomers for analysis. Geodesists want to know from radio astronomers, whether "our markers" at the edge of the universe behave properly.

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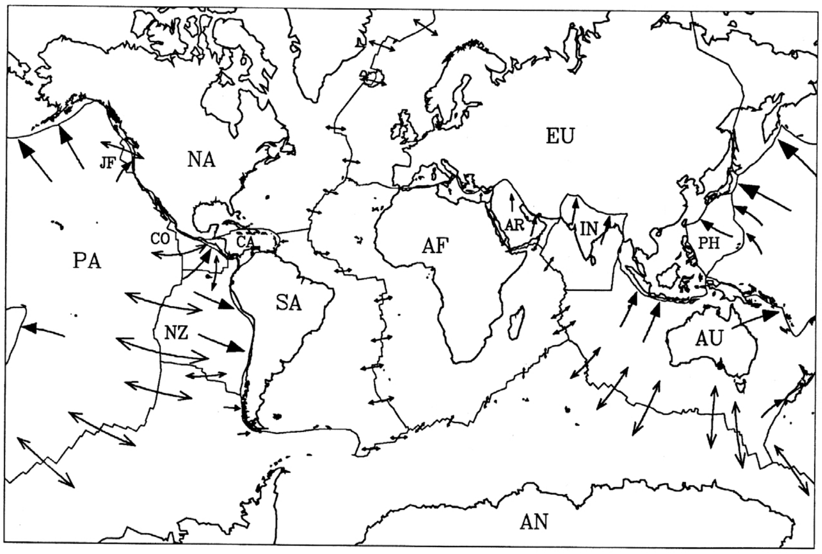


Figure 6: Plate motions and assumed geometry for the NUVEL-1 global relative plate motion model. The length of the arrows shows the displacement if the plates were to maintain their present relative angular velocity for 25 million years. Plate divergence is indicated with double headed arrow, convergence with one headed arrow. Plate boundaries are assumed to be ideal narrow.

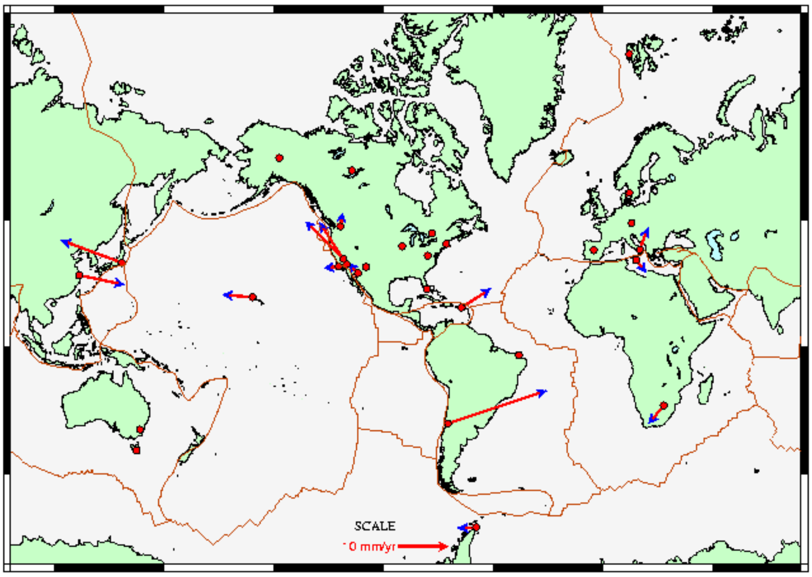
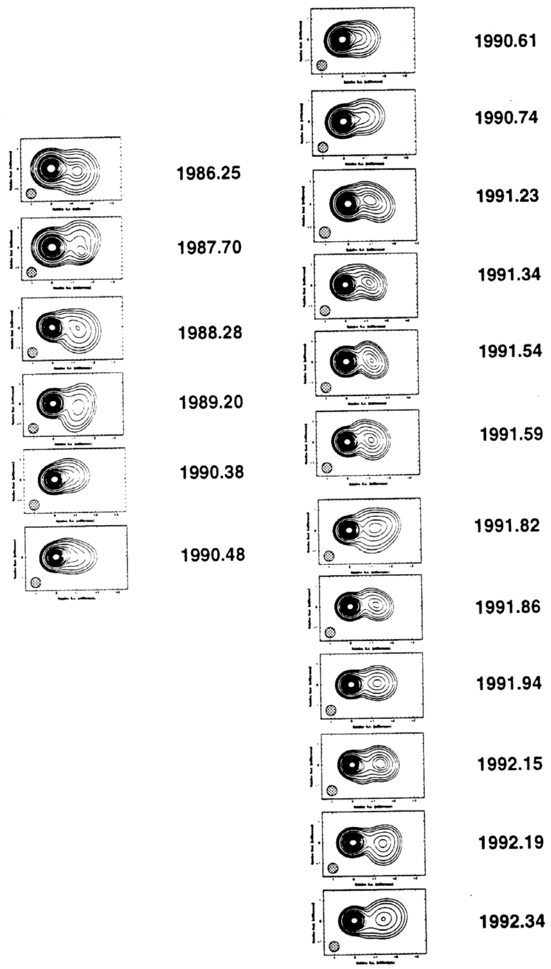


Figure 7: VLBI-site velocity residuals showing the discrepancy between the geophysical model NUVEL-NNR1A spanning 25 million years and the VLBI-results spanning 15 years.



The figure shows 18 modelfits of 1803+784, calculated for the inner 2 mas on the basis of IRIS and IRIS-S VLBI data. Contours are 1, 2, 5, 10, 17, 25, 35, ..., and 95 % of the peak brightness. The convolving circular beam is 0.5 mas, the rectangles are 5 mas × 3 mas in size.

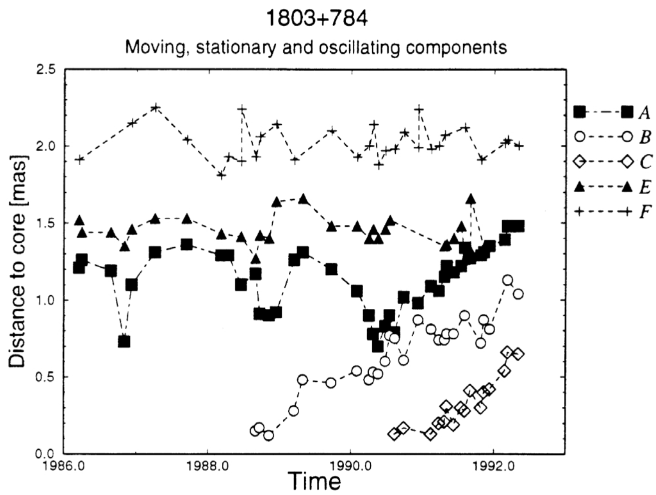


Figure 8: Structure evolution of the inner $2mas$ separation to the core 1803+784 shown for the period of 1986.2 to 1992.34.A and E represent oscillating components, B and C moving components and F stationary component. Error of the relative core separations is typically $\pm 0.15mas$.