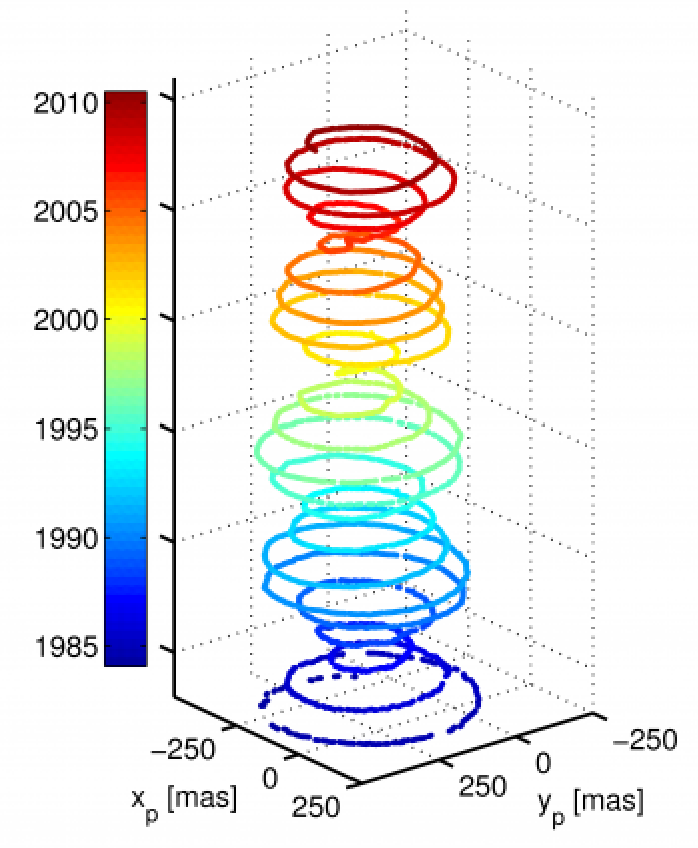
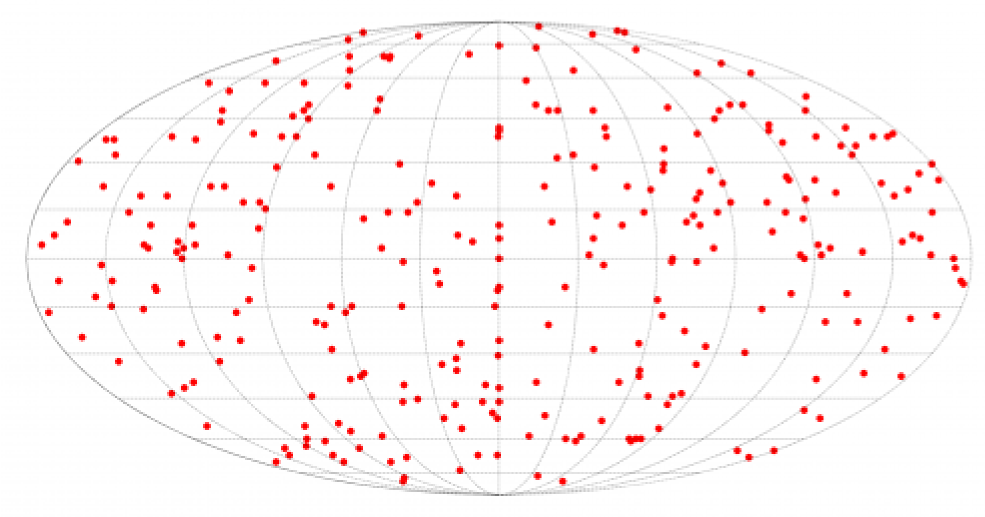
Results from geodetic VLBI and the International VLBI Service for Geodesy and Astrometry (IVS)

The Very Long Baseline Interferometry (VLBI) technique has been employed for more than 30 years in geodesy, geophysics, and astronomy, and results of geodetic VLBI have been presented and interpreted in a multitude of publications by hundreds of authors. During the first two decades, most of the scientific and operational activities were organized through national or bi-lateral agreements, only, which was not a basis sufficiently strong for carrying out VLBI sessions in global networks. In 1999 the International VLBI Service for Geodesy and Astrometry (IVS) was established to coordinate the global VLBI components and resources on an international basis. All international collaboration, in accordance with the IVS terms of reference, is based on a standing call for participation that was first issued in 1998. Any institution that is prepared to participate in IVS activities may join at any time after getting accepted by the IVS Directing Board (Schl￾üter & Behrend, 2007). The inauguration of the IVS took place in March 1999, and the first meeting of the Directing Board was held at the Fundamental Station Wettzell, Germany. The IVS was approved as a service of the International Astronomical Union (IAU), of the International Association of Geodesy (IAG), and of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS); the latter was dissolved in 2010 and replaced in 2011 by the World Data System (WDS). According to its terms of reference, the IVS is an international collaboration of organizations that operate or support VLBI components for geodetic and astrometric applications. Specific goals are to provide a service to support geodetic, geophysical, and astrometric research and operational activities, to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique, and to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system. Since 2003 the Global Geodetic Observing System (GGOS; Plag & Pearlman, 2009) has been developed as a main component of the IAG, and the IVS provides an essential contribution to it (Schl￾üter & Behrend, 2007).

'Official IVS products' are the realization of the Celestial Reference Frame (CRF) through the positions of extragalactic radio sources, the maintenance of the terrestrial reference frame (TRF), such as station positions and their changes with time, and the generation of series describing the Earth orientation (see table below). Geodetic Very Long Baseline Interferometry (VLBI) is the only space geodetic technique that allows the observation of the full set of Earth orientation parameters (EOP), and it is unique in providing Universal Time (UT1) as well as celestial pole offsets over longer time spans. The figure below depicts polar motion estimates as determined from VLBI observations since 1984 with the Vienna VLBI software VieVS (Böhm et al., 2011). As mentioned above, the IVS plays a key role within GGOS and thus all IVS products are also considered GGOS products, today.

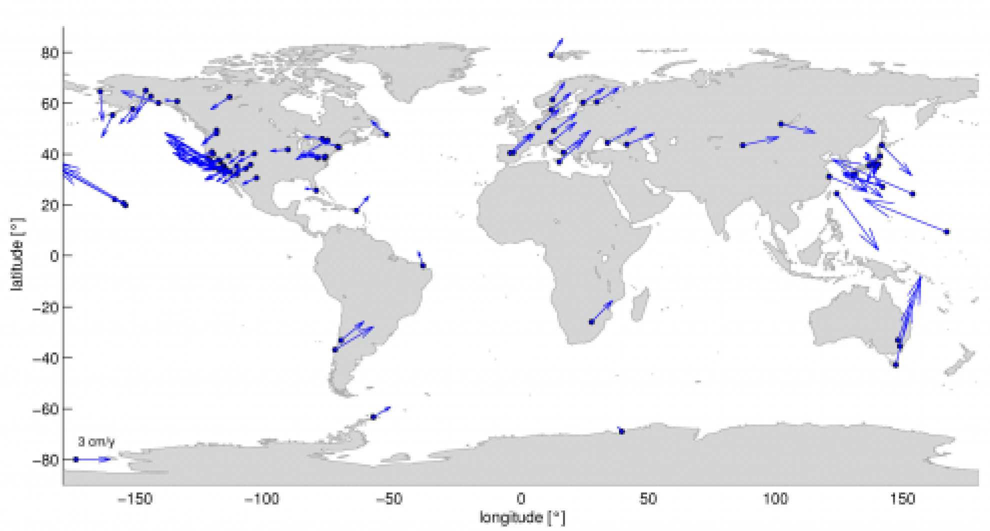


Moreover, VLBI is the only technique for the determination of the International Celestial Reference Frame (ICRF). The International Celestial Reference Frame (ICRF1; Ma et al., 1998), defined by positions of 212 compact radio sources (out of in total 608 radio sources), was the first realization at radio frequencies. Since its approval in 1997 by the IAU, the IVS has been in charge of the VLBI realization. At the XXVII General Assembly in 2009 the IAU adopted the ICRF2 including the positions of 3414 compact radio astronomical sources. This is more than five times the number of sources in the ICRF1 (or its later extension, the ICRF1-Ext.2). The noise floor of the ICRF2 is at the level of 40 $\rm \mu$as and the axis stability at the level of 10 $\rm \mu$as (Fey et al., 2009). The ICRF2 has 295 defining sources with an equal distribution, in particular in the Southern celestial hemisphere, and smaller source structure effects, both weaknesses in the ICRF1 (Fey et al., 2009).



Geodetic VLBI also contributes to the realization of the International Terrestrial Reference Frame

(ITRF) by measuring long intercontinental baselines within global networks. Compared to those space geodetic techniques using satellites, VLBI has the principal advantage that its realization of the ITRF scale only depends on the speed of light c, which is used to transform the delay observables into metric units. There exists no evidence at all that during the last three decades a bias or rate of this conversion has occurred due to technical reasons. The Figure below illustrates the horizontal velocities of the VLBI stations included in the VTRF2008 (Böckmann et al., 2010), the VLBI contribution to the ITRF2008 (Altamimi et al., 2011).



Products	Specification	Status 2010
Polar motion x_p, y_p	Accuracy	50-80 {μ}as
	Product delivery	8-10 days
	Resolution	1 day
	Frequency of solution	~3 days/week
UT1-UTC	Accuracy	3-5 {μ}s
	Product delivery	8-10 days
	Resolution	1 day
	Frequency of solution	~3 days/week
UT1-UTC (Intensives)	Accuracy	15-20 {μ}s
	Product delivery	1 days
	Resolution	1 day
	Frequency of solution	7 days/week
Celestial pole dX, dY	Accuracy	50 {μ}as
	Product delivery	8-10 days
	Resolution	1 day
	Frequency of solution	~3 days/week
TRF (x, y, z)	Accuracy	5 mm
CRF (α,δ)	Accuracy	40-250 {μ}as
	Frequency of solution	1 year
	Product delivery	3 months

The table above provides a summary of current IVS main products (Schlüter & Behrend, 2007). Observations of geodetic VLBI have been carried out for more than three decades providing a basis for the precise determination of geodynamic and astronomical parameters including their long-term variations. For example, VLBI can determine Love numbers h and l of the solid Earth tides model

(Spicakova et al., 2010), ionosphere models (Hobiger, 2006), or troposphere parameters. The long-term VLBI zenith wet delays are of interest for climatologists because they contain information about the precipitable water above the stations for their complete history (Heinkelmann, 2008); they can also be used to validate troposphere parameters from other space geodetic techniques (Snajdrova et al., 2005, Teke, 2011). Another interesting phenomenon, which can be observed by VLBI, is the gravitational deflection of radio waves by the solar gravity field according to general relativity. As described in the Section about relativistic models, radio waves are subject to space-time curvature caused by any massive body (in our solar system mainly those by the Sun has to be considered but also that one by Jupiter for close approaches). At the elongation angle of 2.5° to the Sun, which was the minimal angle of VLBI observations till 2002, the differential deflection reaches 150 mas (Robertson, 1991) causing a significant effect on the observed group delays. With respect to the noise floor of source coordinates, which is about 40 μas for the ICRF2 (Fey et al., 2009), analysis of source observations in the vicinity of the Sun allows the determination of the post-Newtonian parameter γ ('light deflection parameter') characterizing the space curvature due to gravity. Although since 2002 the VLBI observations are scheduled for a minimal angle of 15° to the Sun, the gravitational deflection still influences the measurements significantly and the most recent VLBI global solutions provided γ with a precision of 1×10^{-4} \citep[][2011]{lambert2009}. The series of VLBI data is also sensitive to a possible acceleration of the solar system barycenter which might cause a secular drift of aberration with a magnitude of $4\ \rm \mu as/year$ (Sovers, 1998, Titov, 2010). Furthermore, the solar system motion relative to the cosmic microwave background might produce a dipole pattern that decreases with red shift (Titov, 2010).

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