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VLBI Geodesy: Observations, Analysis and Results

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1. Introduction

Besides the Global Navigation Satellite Systems (GNSS), Satellite and Lunar Laser Ranging (SLR, LLR) and the Doppler distance measurement technique DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), Very Long Baseline Interferometry (VLBI) is one of the space-geodetic techniques. In addition to the aforementioned, satellite missions such as radar and laser altimetry and geodetically used components of gravity field satellites in particular CHAMP (CHAllenging Mini satellite Payload), GRACE (Gravity Recovery And Climate Experiment), and GOCE (Gravity field and steady-state Ocean Circulation Explorer) can be counted to the space-geodetic techniques. In radio astronomy VLBI is a technique for astrophysics and astrometry. The later has many things in common with geodetic VLBI; only the schedule varies among terrestrial and celestial motivated observing sessions in terms of the number of observed radio sources as well as the number and sequence of observations to radio sources. Together with geodynamics, oceanography, glaciology, meteorology, and climatology, geodesy provides the metric basis for interdisciplinary research within the geosciences.

In this chapter geodetic VLBI is introduced. Section 2 describes the fundamentals of the VLBI technique up to the provision of observables. Then sections 3 and 4 give an introduction to the analysis of the various observables and the derived operational and scientific results. The chapter finishes with remarks and conclusions on the current and future role of geodetic VLBI.

2. VLBI technique

The VLBI system can be described by the following components:

i.   the astronomical object, the radio source,
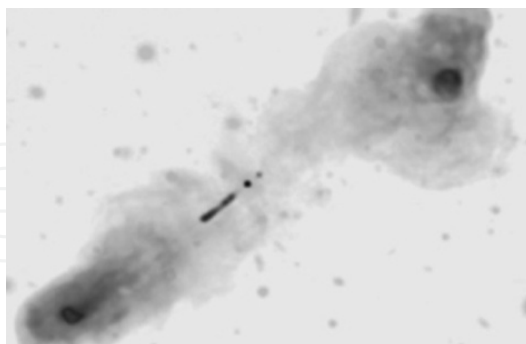
ii.   the propagation of radio waves, the media of propagation of the electromagnetic wave, in particular the Earth's atmosphere,

iii.   the antenna- and receiver system, the mechanical and electronic instrumentation,

iv.   the Earth as being the carrier of the interferometer baselines formed by antenna pairs,

v.   the correlator, and

vi.   the analysis of VLBI observations, i.e. the application of physically motivated mathematical models through the software based on the objective and subjective decisions of the operator(s).

In spite of the large parts in common for the analyses, the scientific aims of astrometric and geodetic and those of astrophysical VLBI significantly differ. While radio astronomy aims to investigate a large variety of astronomical objects and their astrophysical characteristics, geodetic and astrometric VLBI focusses on precise point positioning and derivates, such as the accurate determination of very long distances on Earth, plate motion, or Earth orientation. In the upcoming sections I will describe the various system components in some more detail, necessary for the understanding of the scientific results obtained by geodetic and astrometric VLBI.

2.1. Space segment: radio sources

While astronomical VLBI deals with a large variety of objects, such as supernovae, pulsars, blazars, flare-stars, areas of star formation like globules, OH- and H_2O-maser sources, close and distant galaxies, gravitational lenses, starburst-galaxies, and active galactic nuclei (AGN), geodetic and astrometric VLBI prefers extra-galactic, radio-loud, and compact objects like quasars (quasi stellar radio source), radio galaxies (see Figure 1.), and objects of type BL Lac(ertae). The radio emission of quasars is caused by the accretion of mater into a black hole in the center of the so called host galaxy, where the spectrum is generally dominated by optical, ultra-violet or X-ray emission. During their fall into the black hole matter and electrons are relativistically accelerated. Thus, besides a smaller amount of thermic radiation the natural radiation of radio sources is due to the synchrotron effect. This radiation has a number of beneficial characteristics, such as high intensity and continuity, i.e. not distinct individual spectral lines are emitted but a noise over a broad bandwidth. Quasars contain extreme radio-loud AGNs dominating the emission of their host galaxies. Radio galaxies contain or at least contained an AGN as well, for without the existence of such a center the formation of the observed mater outflow (jets) and radio bubbles (lobes) could not be explained. Around the gravitating center of these objects usually there is a dust torus. The difference between a quasar and a radio galaxy is due to the geometry of observation. Quasars are radio galaxies where the edge of the dust torus obscures the AGN in the line of sight of the observer (Haas & Meisenheimer, 2003). Objects of type BL Lac belong also to radio galaxies (Tateyama et al., 1998). For this type of object the angle between the line of sight and the direction of the jet are very small, i.e. one is looking into the jet. While the physical characteristics of the astronomical objects are still subject of scientific discussion, their strong emission of noise in a broad radio spectrum is

a fact. For geodesy a radio source has to fulfill a number of criteria to be useful as a celestial reference point.

Figure 1. Negative black-white image of radio galaxy 3C219 (0917+458) from a superposition of radio and optical images (NRAO/AUI/NSF). The black dot in the middle shows the AGN.

The brightness, i.e. the intensity of the radiation has to be strong enough at the observed frequency bands. Depending on the antenna characteristics, the minimum lies around 0.01 Jy (Jansky; 1 Jy = 10^{-26} J m^{-2}). This condition has to be fulfilled to achieve an appropriate signal to noise ratio (SNR). The average intensity is 0.38 Jy in X-band and 0.47 Jy in S-band, the two so-called NASA (National Aeronautics and Space Administration, USA) frequencies of geodetic VLBI. The maximal intensity of a radio source may reach 20 Jy in both bands. So far about 4500 sources have been observed by geodetic VLBI. The number of compact bright (intensity > 0.06 Jy) radio sources is expected to be about 25,000 (Preuss, 1982) and thus the number of observable astrometric radio sources is by far not exploited. Besides, the intensity of the radio flux should not vary too much with time to enable a continuous observation.

The compactness, i.e. the spatial extension of the intensity maximum, specified through the angle diameter of the radio source core, has to be smaller than the intended coordinate, declination and right ascension, precision. Since only a very little number of radio sources is ideal compact in X- and in particular in S-bands, the sources show an intrinsic structure within the angle diameter and, consequently, structure corrections of the observations need to be considered (Charlot, 1990). Neglecting the structure would lead to an average error of about 8 ps (2.4 mm) on the group delay observation (Sovers et al., 2002).

The maximum of intensity within a radio source would ideally not shift among the observed frequencies. This effect is, however, in general not fulfilled and the observed position varies up to 700 μas within a source depending on the frequency. For geodesy/astrometry it does not matter whether the core frequency shift is caused by actually different locations of emission or by self-absorption of the object. A structure correction has to be evaluated depending on the observed frequencies; in our case a dual-frequency structure correction (Charlot, 2002). For comparison and for providing a link to catalogues in other, e.g. optical frequencies, the inclusion of radio optic counterparts is another criterion for choosing reference sources. Thus, some radio sources are observed for this purpose when the position of the optical counterpart is known even if other reference point characteristics are not optimal.

The stability, i.e. the temporal invariability of the position of the intensity maximum, has to be given to a certain amount and the radio source should not exhibit significant proper motions or parallaxes. Considering the very large distances of Earth-bound or near-Earth baselines to extra-galactic objects, the two later conditions are evidently fulfilled in a sufficient way. Nevertheless, several radio sources show significant variations of the topology of their intensity maximum. The emission areas of most of the radio sources are not ideal symmetric and centered at the core, but elongate with a bright component at the beginning of a diffuse tail: core-jet-structure. Fortunately, only a few radio sources show significant deformations of their topology up to 300 μas. Besides the radio images, which allow for astrophysical modeling of the structure variations, mathematical modeling of source coordinate time series is achieved through statistical methods such as Allan-variance or hypothesis testing. While the statements about the specific structure depend on the number and quality of the radio images and the astrophysical assumptions, the statistical methods rely on the number and quality of the delay observations and the de-correlation of source and other parameters. The two stability criteria have found to be conflicting in some cases (Moor et al., 2011).

For the realization of radio catalogues, a repeated observation of the radio sources and thus an appropriate visibility from Earth-bound baselines is necessary. This criterion competes with the desired geometrical distribution of the radio sources, which ideally aims for an evenly and consistently sky coverage.

2.2. Propagation media: Space-time, particles, and electrons

On its way through space-time the radio wave might by affected not only by space curvature, but also by charged and neutral particles. According to the distance from Earth, these effects can be divided into inter-stellar effects, which are to a large extend ionizing effects, gravitational effects through our solar system bodies, and ionizing and delaying effects through the atmosphere, ionosphere and neutrosphere of Earth.

Little is known about inter-stellar impact on VLBI group delays. Since VLBI is an interferometric technique, all effects, which are common to both interfered signals are absorbed by the clock model and consequently not visible in the observation. A large part of the inter-stellar propagation media is assumed to have large spatial extend with little variation on the spatial scales of Earth baselines of up to about 12.000 km. Nevertheless, if VLBI observations would be ionized through inter-stellar media, a comparison of VLBI-derived ionospheric delays with those obtained by other space-geodetic techniques, e.g. GNSS, would be appropriate for investigation. In our comparisons (Dettmering et al., 2011a) during two weeks and another separate day, we found no evidence for additional ionization besides the one caused by Earth's ionosphere. Of course the comparisons should be extended to all available data.

While the radio waves propagate through our solar system, the distances to massive objects can get considerably small and the space-curvature may significantly affect the two signals in a different way. For the history of VLBI observations and the precision of 1 ps of the current theoretical VLBI group delay model, called the consensus model, the effects of Sun, Earth and in some cases Jupiter have shown impact on the results. For Sun and Earth the effects of space-curvature on group delays, the so-called Shapiro-delay, are to be considered not only for a

particular geometry of the observation. In the case of Earth, the gravitational delay becomes theoretically maximal, if one antenna observes in zenith and the other antenna at zero degree elevation. Due to the largest mass in the solar system the gravitational delay in the vicinity of Sun has to include another post-Newtonian term. At the limb of Sun the delay can reach 169 ns (as seen from a 6000 km baseline) and it is still about 17 ps almost at the opposite direction (175 degree away from the line of sight from an 6000 km baseline). The higher order term in the vicinity of Sun is about 307 ps at the limb and with 6 ps still significant in one degree distance to the heliocenter; but then it drops considerably fast. For Jupiter and the other solar system planets, corrections would be only necessary, if the ray path is almost in the direction of the object, i.e. grazing the limb of the object. The gravitational delays by the various massive bodies can be finally added by superposition and are usually considered in the theoretical delay model.

By far the largest contributions on the delay observable due to propagation effects are caused by the Earth's atmosphere. For electromagnetic waves the modeling of the effects can be conveniently separated into dispersive (frequency dependent) and non-dispersive (frequency independent) parts. The dispersive characteristics of ionosphere are the main reason for dual-frequency observations in geodetic VLBI. Radio observations are delayed by the ionosphere in the order of several tens of meters, while the neutrosphere's contribution is around 15 m. Both are primarily depending on the elevation angle of the observation, since the path lengths through a spherical shell is approximately proportional to the sine of the elevation angle. The difference between the atmospheres is, that the ionospheric effects can by reduced to mm precision by dual-frequency calibration, while only the hydrostatic part of the neutrosphere, about 90% of the neutrosphere delay, can be effectively reduced, if the surface air pressure at the location of the observatories is accurately known. The remaining non-hydrostatic part has to be estimated (Dettmering et al., 2010).

2.3. Ground segment: radio telescopes and further instrumentation

For radio telescopes one can primarily discern single dish antennae and multi dish antenna arrays or cluster, which are arranged in a certain configuration, e.g. along a straight line, in star formation, Y-or T-form. While the arrays, connected via phase-stable cables, are typically used for image reconstruction in astronomical VLBI, single dish antennae are widely distributed for geodetic and astrometric purposes. Nevertheless, the application of antenna arrays has been investigated for geodetic purposes as well (Saosao & Morimoto, 1991). Geodetic VLBI antennae (see Figure 2.) are usually full steerable constructions made of steel with a concrete foundation attached to a fixed point of geometric reference. In the 80s and 90s of the last century there were a number of mobile VLBI stations active: the U.S. American systems MV1, MV2, and MV3 (Clark et al., 1987), which were eccentrically installed above one of about 40 platforms (Ma et al., 1990). The German Transportable Integrated Geodetic Observing system (TIGO, Hase, 1999) was after a test phase at Wettzell, Germany, steadily installed at Concepción, Chile, for improving the terrestrial network of core IVS VLBI sites. With the advent of GNSS, the application of mobile VLBI has been ceased, since it became economically unviable.

Most VLBI antenna reflectors are of Cassegrain type. In addition to a parabolic main reflector, the Cassegrain antenna has a sub reflector at the focal point of the main reflector, which is of convex hyperbolical shape. One of the focal points of the sub reflector lies in the middle of the main reflector. After the radio signal has been focused in the opening of the main reflector, covered by a feed horn, it is not immediately received but undergoes several electronic conversions, so-called heterodyne reception. The situation of the sub reflector may lead to shadowing effects of the main reflector. The inflicted signal loss, however, is negligibly small (Rogers, 1991). For gaining a sufficient signal to noise ratio, the antenna diameter and directivity play a significant role. Additional radio noise sources, such as atmospheric noise and the noise emitted by the temperature of the electronic components have to be suppressed. The received signal can be disturbed by transient signals, e.g. from radio or television broadcast, so-called radio frequency interference (RFI), in particular at S-band, which may ultimately lead to complete loss of one or more channels. Such cases have been increasingly reported depending on the environment, e.g. by Sorgente & Petrov (1999) at Matera, Italy. To keep the thermal noise as small as possible parts of the electronic are cooled down to a few degrees Kelvin, e.g. at the Radio Telescope Wettzell, Germany, using liquid Helium. For a low-loss focus of voltage the surface of the antenna has to be manufactured with a very high precision. The requirement for precision is about 0.05 of the wave length (Nottarp & Kilger, 1982).

Figure 2. The RTW (Radio Telescope Wettzell), a 20m diameter geodetic VLBI antenna at the Geodetic Observatory Wettzell, Germany (BKG/FESG), has observed the largest number of observations within IVS campaigns

Azimuth-elevation, X-Y, and polar or equatorial mounts can be found for geodetic VLBI systems. Most of the polar mounted antennae belonged to other programs and were used for other purposes before. The deep space network antenna at Hartebeesthoek, South Africa, for example, was constructed by NASA for tracking deep space vessels but later equipped with geodetic receivers and a precise timing unit and thus rearranged for geodetic purposes. The geodetic schedules require relatively large rotations of the telescopes switching among widely separated radio sources covering large azimuth and elevation angle distances. Therefore and to achieve a sufficient SNR, mid-size, about 20 m diameter, telescopes have proven to be

optimal for geodetic schedules. Dishes with such dimensions of course considerably deform depending on thermal and wind-driven environmental conditions as well as due to gravitational sacking at various elevation angles. Variations of the telescope geometry may cause defocussing and thus the loss of the signal. In particular large steerable telescopes, such as Effelsberg, Germany, need to move the feed horn and with it the focal point of the reflector according to the elevation angle of the observation to remain focused. With smaller telescopes the deformations may not lead to the total loss of signal but the environmental effects may significantly distort the VLBI observable. There are empirical models, material constants, and antenna dependent data available for thermal deformations (Nothnagel, 2008), so that for most of the geodetic antennae this effect can be corrected. Only those antennae covered by a radome need to be treated individually, for the inside radome temperature is usually not available via IVS. For gravitational deformation there are models available, too, e.g. published by Sarti et al. (2010), but there are not all relevant antenna-dependent data collected for the consistent application. Gravitational deformations are larger for primary focus antennae, i.e. for those antennae, where the relatively heave receiver is located in the focus of the main reflector, and those are rather the minority of geodetic antennae. There are no models for wind induced deformations available. In case of strong winds, the telescope usually stops observing and moves to a safety position.

The VLBI reference point, where the VLBI measurements actually refer to, is usually an immaterial invariant point located at the intersection of the telescope axes. Since this point is usually not directly accessible, it needs to be eccentrically realized, e.g. through indirect measurements from external reference markers (Vittuari et al., 2001; Dawson et al., 2007). Those eccentric reference markers allow the access and maintenance of the VLBI reference point for other space-geodetic or engineer surveying techniques. The later are usually applied to determine the distance between reference points of various space-geodetic techniques, called local ties. The local ties, after transformation into the Cartesian geocentric system of the space-geodetic techniques, are one of the most important issues for the realization of multi-technique terrestrial reference frames, such as the current conventional International Terrestrial Reference Frame, ITRF2008 (Altamimi et al., 2011). The primary axes of the telescopes do practically not intersect. The size of the antenna axis offset can be only a few millimeters or can reach up to several meters (Nothnagel & Steinforth, 2005). For its determination, in the best case, there are measurements by precise engineer surveying methods available; otherwise it has to be estimated from VLBI observations.

The antennae are driven and controlled by the field system, a LINUX-based software for the movement of radio antennae (Himwich, 2000), which allows the automatic control during a VLBI-experiment scheduled in advance. The cable winding needs to be considered as well, since the antenna can only limitedly turn into one direction. New approaches of automized, semi-unattended antenna control are under investigation as well (Neidhardt et al., 2011).

With the aforementioned antennae it is in principle possible to receive frequencies between about 0.4 and 22 GHz. For geodetic and astrometric VLBI, the application of the so-called NASA-frequencies of about 8.4 GHz (X-band) and 2.3 GHz (S-band) became accepted. With the dual frequency reception, channels of a few to several hundreds of MHz around the mid-
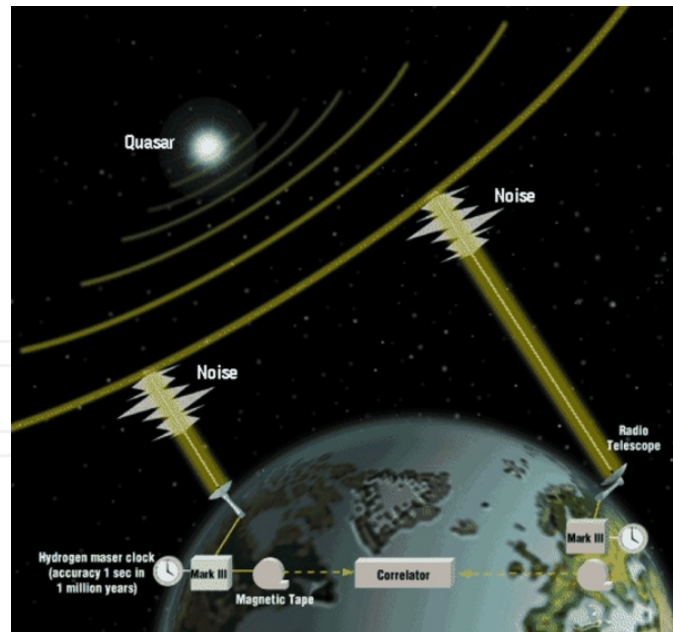
band frequencies are band pass filtered from the continuum noise of the radio source and then individually processed. The incoming radio signal, the so-called received frequency, is initially polarized and then amplified. Thereafter it is down converted to an intermediate frequency of about 300 MHz at the front end of the antenna (Whitney et al., 1976). To keep the data rate small, not the complete bandwidths but several channels of a few MHz are processed only. The individual channels are later on synthesized to a larger effective bandwidth applying bandwidth synthesis (Rogers, 1970; Hinteregger et al., 1972). Via a coaxial cable the signal is propagated to a nearby control building, the so-called back end, where further data processing steps take place until the signal is finally recorded. After the conversion to base band frequency, the signal goes through a formatter, where time stamps of a local oscillator are superimposed. This video signal is then sampled and quantized, so that the digital value is represented by e.g. 1-bit sampling. It is also possible to digitize the signal with higher bit assignment. Until the Mark III VLBI-system the gained digital signals were recorded onto magnetic tapes. Thereafter, applying Mark IV or newer VLBI-systems, the data are saved on hard disks. The requirements for data recording rates were and are still very challenging.

The data storage media, magnetic tapes or hard disks, are then shipped to a central processing unit, the so-called correlator, for further processing and determination of observables. Still under development is the step away from storage media towards e-VLBI, i.e. real time VLBI with data send via broad band cables (Whitney & Ruszczyk, 2006), such as via the internet. Unfortunately, this method of data exchange has to compete with commercial users and can thus become very expensive. In addition, many VLBI-antennae were intentionally built at rather remote places, so that cables in particular at the last few kilometers are often not available and would have to be laid only for this purpose. That's why e-VLBI has been successfully tested, but is often not applied for routine IVS VLBI-experiments at all the participating sites.

For measuring effects through the electronic components and instrumentation, an artificial signal is injected at each antenna system, with which variations of the signal phase can be detected, so-called phase calibration. The calibration signal is induced by a local oscillator at the front end in form of equally spaced pulses of 1 µs separation. The artificial signal undergoes the same signal way than the received signal. Since amplitude, phase, and frequency of the artificial signal are known, it is possible to reconstruct the effects on the received signal. To detect frequency depending characteristics of the instrumental effects, the phase calibration is done for each frequency channel separately (Whitney et al., 1976; Corey, 1999). Besides the phase calibration, the cable delay is calibrated as well, i.e. the delay of the signal between the epoch, the signal passes the VLBI reference point and the epoch it is actually recorded. Another source of error on the VLBI observable is due to polarization leakage. Polarization leakage arises from unavoidable imperfections in the construction of the polarizer. It corrupts the observed phase in a way that can depend on frequency.. So far polarization has shown to affect the geodetic observable in the order of 1.6 ps for 90% of the observations, an effect, which can still be neglected (Bertarini et al., 2011). Nevertheless, for the VLBI2010 observing system, polarization will become an issue.

2.4. Interferometer and interferometric principle

The wave length of the center frequencies, i.e. the geometric mean of the lower and upper cutoff-frequencies, in X- and S-band are about $\lambda_X = 3.6$ cm and $\lambda_S = 13$ cm. Since the bandwidths are rather small compared to the center frequencies, the frequency bands are sufficiently represented by their center frequencies. If observations were restricted to be carried out by a single antenna, angle resolutions of about 100 as (seconds of arc) could be achieved. By connecting two or more antennae of similar type on a baseline (Figure 3.), it is possible to synthesize a much larger antenna diameter. The angle resolution on an average baseline of about 6000 km, e.g. Westford, USA to Wettzell, Germany, already reaches 1.2 mas (milliarc-seconds) and is thus several orders of magnitude more precise than the resolution obtained by a single antenna. Through such a connection of antennae, called interferometer, however, not radio images, but patterns of interference are provided. Interference is excited, if the received signals fulfill the coherence condition. Temporal coherence of equally polarized radiation expressed in simplified terms means that the phase is temporarily invariant. Besides temporal coherence, which depends on the different lengths of the signal paths, spatial coherence plays a significant role as well. Adhering spatial coherence the diameter of the radio source needs to be rather small, optimally point like. Variations of the interference caused by spatial extension of the radio source are the basis for investigations of the source structure in radio astronomy. To separate spatial and temporal coherence, the frequency bandwidth has to be much smaller than the observed frequency.

Figure 3. Scatch of a VLBI delay and the basic instrumental components of a Mark III VLBI system taken from the NASA/GSFC brochure "VLBI – measuring our changing Earth"

Considering the recorded bandwidths of a few hundreds of MHz compared to the observed frequencies of 2.3 and 8.4 GHz, the separation is in principle possible. For VLBI observations

the coherence has to be realized through local frequency normals. Synchronization of the normals can be approximately achieved via time transfer e.g. by the GPS system. With local frequency normals, however, it is not possible to maintain the coherence during the whole observation session, yet during smaller time spans of a few minutes. This short coherent time span is usually sufficient to integrate a single observation, called a scan (Thompson et al., 2001). VLBI's requirements for frequency stability are very demanding, but only during these short time spans of up to about 1000 s (17 minutes). Hydrogen-maser normals have proven to deliver highest frequency stability over the required coherent time span and are thus installed at geodetic VLBI observatories. The imprecision through the synchronization and drift of the various masers is usually parameterized and estimated along with the other astrometric, geodetic and auxiliary parameters (see section 3). It is an inherent characteristic of the inter-ferometric technique that only those quantities affecting the interfering signals in a different way are visible in the observation, i.e. the interferometer is independent of effects common to both signals.

2.5. Earth: Carrier of interferometer baselines

The temporal coherence condition is generally not fulfilled because of the motion of Earth during observation. The geometry of the baseline and the radio source is continuously changing, e.g. due to Earth rotation. The phase of the received signal, therefore, slowly varies with time. As a consequence, not a constant interference frequency, but a slowly varying fringe frequency mainly caused by the differential Doppler-effect of Earth rotation is observed during the finite duration of an observation.

The radio telescopes forming the baselines are quite stably attached to the underlying rock bed through their mount, a construction mainly made of steel and concrete. Earth's surface, however, is not stable. On the contrary, the lithosphere is subject to a variety of deformations. Some of the deformations are rather constant, secular, or periodical. Others are individual, episodic, and discontinuous, e.g. during and after a seismic event. Occasionally a significant antenna repair has to take place, where the antenna is lifted from its rail. In spite of the usually very carefully executed procedure, such a repair typically leads to a displacement of the VLBI reference point of a few millimeters. Local deformations have been observed at some sites, e.g. through increasing water abstraction or season-depending irrigation. Secular variations, such as the slow geodynamics of the lithosphere, in particular recent crustal motions, plate motions, and postglacial rebound, are the subject of plate motion models, such as the Actual Plate KInematic Model APKIM (Drewes, 2009). Those secular drifts of the plates are almost exact linear within time scales of thousands of years and are believed to be driven by the continuous process of sea floor spreading (Campbell et al., 1992). The station coordinate model of current terrestrial reference frames therefore contains at least a position and a linear velocity term for each site. Nevertheless, at the borders between plates, the plate boundaries, significant anomalies with respect to the linear velocities can be found. Stress and strain release at the plate boundaries is also a major origin of earthquakes. Co- and post-seismic lithosphere deformations can only be individually explained depending on the earthquake mechanism. For the very well observed M7.9 Denali earthquake with its epicenter close to Fairbanks,

Alaska, in November 2002, non-linear motions of the VLBI station at Gilmore Creek were successfully approximated by a combined logarithmic-exponential model. The exponential deformation held on for several years after the co-seismic positional jump (Heinkelmann et al., 2008).

Displacements of reference points through tidal and loading deformations occur on much shorter time scales, such as hours, days, months, or years. This group of effects is to such an extent sufficiently understood and described by geophysical models, that it is usually directly reduced from the observations and therefore no contributions appear in station coordinate residual time series. Deformations belonging to this group are:

i.   The solid Earth tides, caused mainly by the external torques of Moon and Sun, where deformations are related to the torques by a set of both, time and frequency dependent, constants, called Love and Shida numbers.

ii.   The loading deformations, which also comprise secondary effects on solid Earth due to interactions among the Earth system's spheres, mainly oceanic tidaly and atmosphere pressure induced, but also seasonal hydrological and snow induced loading deformations.

Besides the deformations of solid Earth and the displacements of attached reference points, the rotation axis of Earth is moving because of the inclination of the rotation axis with respect to the figure axis. The movement of the axis can be expressed with respect to the Earth's surface, i.e. the International Terrestrial Reference System (ITRS) or with respect to quasi-inertial space realized by the Geocentric Celestial Reference System (GCRS). The effects expressed with respect to Earth's surface are separated from those with respect to the celestial frame depending on frequency. By convention all terms around the retrograde diurnal band are addressed with respect to GCRS and the other terms, outside of the retrograde diurnal band, are attributed with respect to ITRS. Finally between ITRS and GCRS the diurnal Earth spin takes places. The terms with respect to ITRS are called polar motion. Besides the main periodically signals with 430 days (Chandler wobble) and annual periods, polar motion shows secular drifts, called polar wandering. Polar wandering is explained by large long-term mass variations inside the Earth system. Such a large mass variation occurred for example through the advance and following melting of glaciers during the last ice age at the end of the Pleistocene, where up to 3 km thick ice sheets covered large parts of Scandinavia, Greenland, and Canada. Since then Scandinavia for example has lifted about 300 m upwards and the global sea level raised about 120 to 130 m. Polar motion causes another group of reference point displacements:

iii. The pole tides, a centrifugal effect due to the secular motion of the mean pole of Earth's rotation axis with respect to Earth's crust, and the ocean pole tides, a second order effect on solid Earth due to the equilibrium response of the oceans with respect to the main periodical signals within polar motion, the Chandler wobble and the annual term.

VLBI is an extraordinary technique for the determination of variations of the Earth rotation velocity. The velocity of Earth rotation shows for example tidally induced variations and a

secular deceleration due to tidal friction in the two-body-system Earth-Moon. With respect to GCRS the orientation of Earth is varying, too, which is called precession-nutation. By continuous monitoring of these quantities models of the Earth interior could be improved. Free core nutation models were derived by Earth orientation parameters determined from VLBI observations. So far a period of about 430 days has been assumed for free core nutation, although some authors consider an interference of two signals with periods around 410 and 450 days (Malkin & Miller, 2007). For the determination of such models one is always bound to indirect methods, since the deepest drilling into Earth crust reached only about 15 km.

Even during the short delay between the receptions of the radio signals at the two VLBI antennae of about 20 ms as seen from a 6000 km baseline, the interferometer significantly moves due to Earth rotation and ecliptic motion. Consequently, the baseline is initially defined at those two epochs, called retarded baseline effect, and has to be referred to one epoch. The motion of the second antenna after the signal reception at the first antenna is accounted for in the theoretical VLBI delay model.

All those effects have a common consequence: each baseline formed by a pair of antennae is not constant but varies with time. Lengths and directions of the baseline vectors can change with respect to Earth's surface and with respect to the radio sources reference frame.

2.6. Correlation: Determination of observables

During correlation the individually recorded digital signals are superimposed for achieving interference whereby the observables are obtained. The equipment with which this process is done is called a correlator. In principle, one can distinguish between hardware and software correlators. While a hardware correlator is limited by the number of magnetic tapes or disks, which can be processed in parallel, the performance of a software correlator depends only on the available computing capacity. Applying modern concepts such as computer clusters or distributed systems and due to the steady improvements and developments of computer hardware, the technical borders of correlators are not yet reached (Kondo et al., 2004; Machida et al., 2006).

A variety of observables can be obtained depending on the purpose of the application. Astronomical VLBI primarily aims for high resolution image reconstruction. Therefore, the fringe amplitudes and phases are the desired observables. The contribution of each telescope is added in such a way as if the whole array would be one single antenna. For geodetic and astrometric VLBI precise group delay and delay rate observables are required. The group delay can be obtained by shifting the interfering signals in the time domain until the maximum of cross correlation is reached. In addition to the cross correlation of the bit streams the fringe rotation mainly caused by the Doppler effect due to Earth rotation, needs to be removed, so-called fringe stopping. This can be achieved by multiplication with sine and cosine terms, so-called quadrature mixing, where the fringe rotating cross correlation signal, which oscillates in the kHz range, is brought to a frequency close to zero. Fringe amplitude and phase can be obtained by summing up or dividing (tangent) the sine and cosine terms, respectively. The fringe frequency, the partial derivative of the phase delay with time, can be tracked for several minutes, as long as one radio source is continuously scanned. Switching among the radio

sources, however, introduces ambiguities, which have to be solved for a phase measurement, called ambiguity solution. The ambiguity problematic can be avoided, if the group delay is used as observable, since the cross correlation function usually shows a unique maximum. The delay rate is the other observable used for geodetic VLBI to fix the ambiguities introduced by the broadband synthesis prior to the analysis of group delays. It can be obtained from the fringe frequency describing the phase drift due to Earth rotation. Since the precision of the delay rate in terms of geodetic target parameters is significantly worse compared to the group delay, it is usually not used itself for parameter determination.

The correlation procedure can be mathematically described through a cross correlation and a Fourier transformation. If the signals are at first cross correlated and then Fourier transformed, the correlator type is called XF-correlator, e.g. the Mark VLBI-systems. Otherwise, if the two mathematical procedures are applied vice versa, it is called FX-correlator, e.g. the VLBA-systems. Both correlator types have advantages and disadvantages (Moran, 1989; Alef, 1989; Whitney, 2000).

2.7. Precision of the group delay observable

The instrumental precision of the group delay from the correlation analysis

$$\sigma_\tau = \frac{1}{2\pi \bullet B_{eff} \bullet SNR} \tag{1}$$

primarily depends on the signal to noise ratio SNR and the effective bandwidth B_{eff} yielded by synthesizing the real observed and correlated channels

$$B_{eff} = \sqrt{\frac{\sum (f_i - f)^2}{N}} \tag{2}$$

where f_i are the channel frequencies ($i = 1, 2, \ldots, N$) and f is their mean frequency. The signal to noise ratio

$$SNR = \eta \sqrt{2 \bullet B_{eff} \bullet t_{int}} \frac{I}{2k} \sqrt{\frac{A_1 \bullet A_2}{T_{R,1} \bullet T_{R,2}}} b \tag{3}$$

is the criterion for a successful observation with $\eta \approx 0.73$ (1-bit sampling) an instrumental loss factor, $t_{int} = 60$ to 1000 s the coherent integration time, I the radio flux or intensity of the radio source, k the Boltzmann constant; $A_{1,2}$ denote the effective antenna areas and $T_{R,1}$ and $T_{R,2}$ are the noise temperatures of the electronic devices (Whitney et al., 1976). Above equations (1-3) describe the sensitivity of the measurement precision first of all to the effective bandwidth, but also to the intensity of the radio source. To observe radio sources with smaller intensities the coherent integration time needs to be quadratically increased to keep the measurement precision using the same equipment. The terms assume that a common system noise is implicitly present, independently at each channel and of the same size. There are, however, a

number of instrumental negative effects, which affect individual channels only. Ray & Corey (1991) therefore discus an extension of the above model through two empirical variables: a scaling factor and an additive constant.

Besides the instrumental precision related to a single observation, the stochastic model of ensembles of VLBI observations can be described not only by the diagonal elements but also by off-diagonal elements in the weight or covariance matrices, respectively. A large variety of covariance models are possible in principle to describe the correlations of the observations among each other (Tesmer, 2004). Among them the modeling of station dependent noise has shown to significantly improve the stochastic of the VLBI equation systems (Gipson, 2007).

3. Analysis of group delays

After the ambiguities from broadband synthesis have been fixed incorporating the delay rate observable, the mathematical model of the analysis of group delays deals with

i. the functional model, i.e. the creation of theoreticals. Simulated observations are calculated for each real observation applying the theoretical VLBI group delay model and a variety of correction models. The theoretical VLBI model used today is called the consensus model and includes all necessary terms to achieve 1 ps precision (about 0.3 mm). As presented at the IAU General Assembly 2012, the IAU Commission 52, Relativity in Fundamental Astronomy, is going to present a new model with 0.1 ps precision, soon. The current conventionally applied correction models are specified by IERS Conventions (2010).

ii. The determination of parameters, which also includes the stochastic of the over-determined problem by modeling the committed errors and the neglected determin-istic systematics. In geodetic VLBI several techniques have been applied for parameter determination: first of all least-squares estimation (Koch, 1997), then least-squares collocation (Titov & Schuh, 2000), Kalman filtering (Herring et al., 1990), and square-root-information filtering (Bierman, 1977).

The deterministic part of the mathematical model, the functional model of the group delay observation τ_{gd}, can be symbolically written as

$$\tau_{gd} = -\frac{1}{c}b'WRQk + \delta\tau_{rel} + \delta\tau_{iono} + \delta\tau_{neut} + \delta\tau_{cable} + \dots \qquad (4)$$

It contains the speed of light c, the baseline vector b', the polar motion matrix W, diurnal spin matrix R, the frame bias, precession-nutation matrix Q, and the radio source position vector k, which depends on the declination and right ascension at epoch J2000.0. The first expression at the right hand side before the relativistic delay correction $\delta\tau_{rel}$, is called geometric delay. Together with the relativistic delay correction the geometric delay is called theoretical delay model; specified e.g. by the consensus model (Eubanks, 1991) in its current conventional form (IERS Conventions, 2010). With the current precision it is sufficient to model the group delay

in a Newtonian way and to add the relativistic implications, the retarded baseline and other special and general relativistic effects, in form of corrections to the Newtonian delay. The first order ionosphere correction

$$\delta\tau_{iono} = \frac{f_S^2}{f_X^2 - f_S^2}(\tau_X - \tau_S) \tag{5}$$

is derived by a linear combination of the single band delays at X- and S-band multiplied by a factor, the ratio of the square of the lower band frequency to the separation of the squared frequencies. Higher order terms can be neglected for the desired precision, (Hawarey et al., 2005). In analogy to this term the measurement error in S-band, which is due to the lower resolution usually larger than the one in X-band, propagates into the X-band group delay. The smaller the factor, the smaller is the error contribution from S-band on the X-band group delay. A wide frequency separation decreases the factor and is, thus, favorable for precision.

Additionally explicitly mentioned are the neutrosphere delay $\delta\tau_{neut}$ and the cable delay $\delta\tau_{cable}$ corrections. The three dots at the end of the above equation denote that there can be further corrections considered. Each of these delays contain two terms, one contribution from the first and one from the second station forming a baseline. If the radio signal first reaches the first antenna, the contribution to the group delay is positive for the second antenna and negative for the first antenna and vice versa. The neutrosphere correction of the i-th station is given by

$$\delta\tau_{neut,i} = \frac{1}{c} \bullet mf_h(e) \bullet zhd + mf_g(e)[cos(a)G_N + sin(a)G_E] \tag{6}$$

where *mf* are mapping functions of the hydrostatic delay (index *h*), or the gradients (index *g*), depending on the elevation angle *e*. The horizontal asymmetry is modeled by the two gradients in north-south G_N and east-west directions G_E depending on the azimuth angle *a*. The above term is multiplied with the factor -1, if i = 1. State-of-the-art mapping functions are derived by raytracing through numerical weather models, e.g. VMF1 (Böhm et al., 2006). The hydrostatic delay in zenith direction *zhd* is direct proportional to the surface air pressure at the VLBI reference point of the specific instrument. An appropriate apriori gradient model should be applied for geodetic VLBI analyses, because the estimated gradient parameters are usually constrained and can thus depend on the apriori values. Besides the apriori gradient model specified by IERS Conventions (2010), the usage of the apriori gradient model determined from the Data Assimilation Office weather model as provided by the IVS Analysis Center at NASA Goddard Space Flight Center (MacMillan & Ma, 1998) can be recommended. The cable delay is measured at each antenna and can be directly applied as taken from the IVS database. The theoreticals calculated in the above described way are subtracted from the observed group delays forming the o-c (observed minus computed) vector.

Before the parameter estimation process, the analyst has to decide on the parameterization, i.e. the definition of the parameters, which shall be determined. According to this decision, the design or Jacobi matrix relating the observations to the parameters is fixed in its overall structure. The entries of the design matrix are the partial derivatives of the observations with
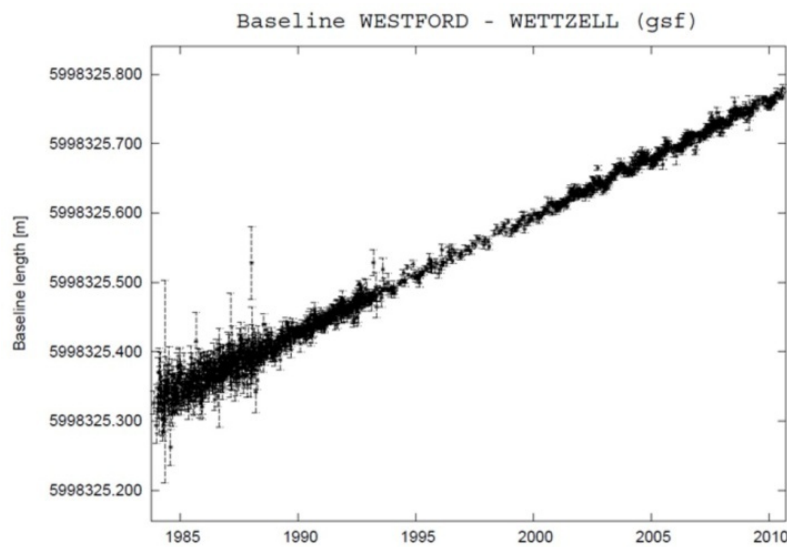
respect to the individual parameters. A large variety of partial derivatives of geodetic and astrometric parameters can be found in Nothnagel (1991) or in Sovers & Jacobs (1996). The row and column ranks of the equation system are extended by the geodetic datum and the pseudo-observations, respectively. The pseudo-observations are constraints on auxiliary parameters, which can be necessary to prevent singularities. The impact of the constraint is governed by its weight, which is chosen by the analyst. With the precision of the group delay as the basis for the weight matrix, the mathematical model is complete and the parameters can be determined.

The aim of the analysis is to produce normally distributed residuals. This implies that all present significant systematics are identified and sufficiently modeled and that the stochastic part contains pure white noise, an assumption of the estimation methods. By robust estimation the normal distribution can be forced to a certain extent. This method, however, practically discards observations violating certain robustness criteria and thus decreases the redundancy of the problem. It also requires some additional operations, what increases the runtime. Nevertheless, both disadvantages are usually accepted considering the advantages of robust estimation (Kutterer et al., 2003). The derived formal errors of the parameters are the outcome of observation and model errors projected into the parameter space by error propagation. Not all the possible error sources are necessarily included and thus the existence of further neglected errors, called omitted errors, can be assumed. Consequently, to obtain meaningful accuracies the type and size of omitted errors have to be assessed and added to the formal errors as well. If a significant error source is known but not considered, the formal errors, which are then actually smaller than the real errors, nust be inflated e.g. by a factor or a constant depending on the assumed characteristics of the omitted errors. Due to the inherent characteristics of VLBI, the baseline repeatability presents a reliable and often-used quality criterion for the performance of the parameter estimation, since it is independent from the geodetic datum. A more detailed overview of the geodetic VLBI analysis is presented by Schuh (2000).

3.1. Coordinates and Earth orientation parameters

VLBI for geodesy and astrometry group delay analyses primarily aim for the determination of terrestrial baselines (see Figure 4.), radio source positions, and the Earth orientation parameters (EOP). These parameter groups can be estimated at the same time. Nevertheless, the design of the observation sessions, specified through the scheduling, which is carried out in either geodetic or astrometric mode, usually optimizes one or two of those three parameter groups. In the standard estimation approach for a single about 24 h IVS session, the auxiliary parameters for clock synchronization and neutrosphere delay and gradient modeling are estimated at the same time. The clocks are already synchronized e.g. via the GPS system time. During the experiment the hydrogen maser normals show some drift and occasionally jumps with respect to each other. A reference clock needs to be defined and the drift of the other clocks can be usually approximated by a second order polynomial with respect to the reference clock. Additional auxiliaries are parameterized as piece-wise linear functions with a temporal resolution of about 30 minutes for stochastic fluctuations of clock and neutrosphere delays and several hours for neutrosphere gradients, respectively. To discriminate between common

rotations of the radio sources and the Earth orientation parameters it is necessary to include no net rotation (NNR) condition equations for the celestial coordinates. Also the polyhedron of terrestrial baselines can be subject to overall rotations, which by convention are to be expressed by the EOP and thus, NNR conditions need to be applied at the terrestrial side as well. To derive network station coordinates instead of baselines both, an apriori set of coordinates and another geodetic datum have to be provided. For deriving geocentric coordinates the apriori values have to refer to the geocenter. This is the case for conventional terrestrial reference frames, such as a version of ITRF. The datum has to constrain the adjustments to the apriori values at least in such a way that the inherent translational ambiguities are appropriately fixed, and then no singularities appear in the equation system.

Figure 4. With its almost 6000 km the baseline WESTFORD (Westford, USA) – WETTZELL (Wettzell, Germany) shows a constant linear increase of about 1.7 cm yr^{-1}, which is due to the motion of the North American w.r.t. the Eurasian plate. The small annual signal is due to unmodelled geophysical effects. The figure is provided by IVS (http://vlbi.geod.uni-bonn.de/baseline-project/) and made of results from the IVS AC NASA/GSFC.
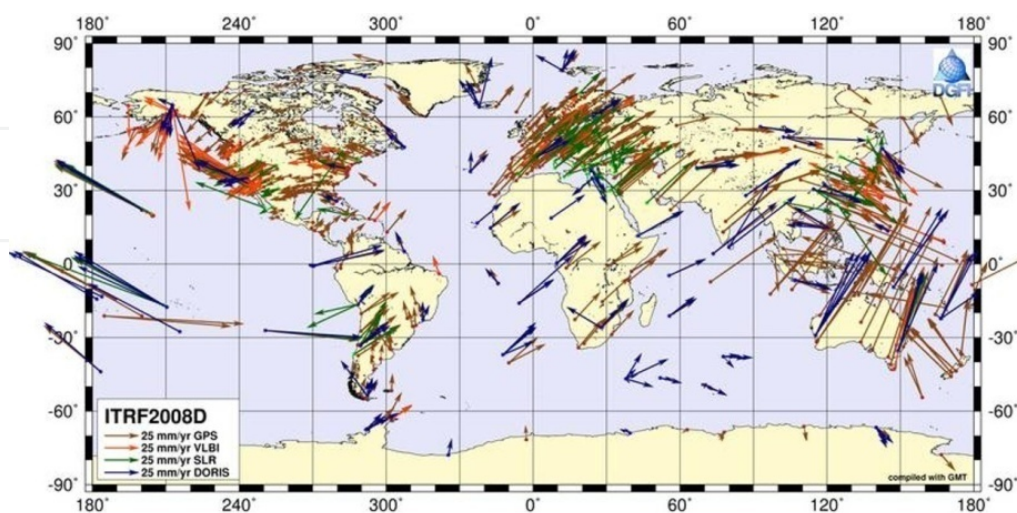
This set of condition equations is called no net translation (NNT). The NNR and NNT equations are the current best non-deforming datum conditions, because in contrast to fixing specific sets of coordinates, all coordinates are adjusted by this approach called free network adjustment. The origin and the orientation of the apriori frames are conserved but only in a kinematic sense. Consequently, due to the imperfect representation of the system through coordinates of its measured objects, there can still be some frame rotations present which cannot be suppressed by this approach. The imperfections of the kinematic non-rotating approach may lead to small differences between kinematically and dynamically non-rotating conditions, which may have to be considered by corrections.

3.2. Reference frames

In contrast to the analysis of a single VLBI session, the complete history of VLBI data are usually analyzed for the determination of reference frames and time series of EOP. If longer time spans
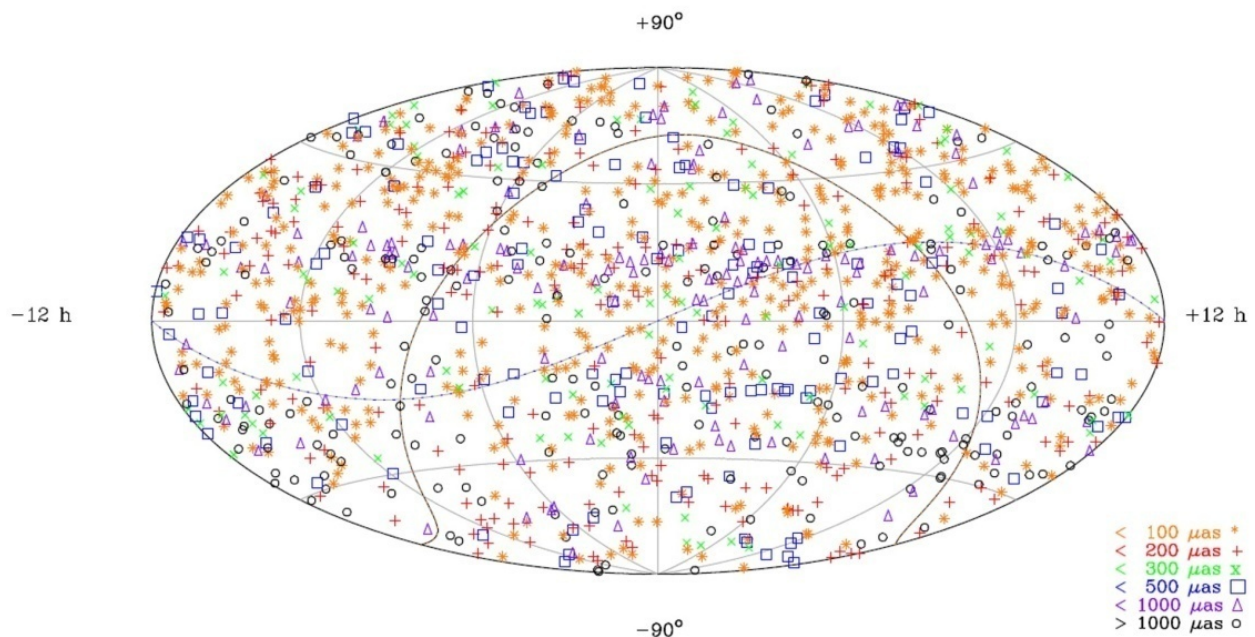
are analyzed, velocities of terrestrial network stations need to be parameterized as well. Consequently, it is necessary to include additional datum conditions for the temporal evolution of both terrestrial NNR and NNT conditions. In principle, a datum gets more reliable, the more datum points are included (Baarda, 1968). For the frame determination, the choice of reference stations, or reference radio sources, respectively, is one of the major tasks. Stations are usually applied as a reference, if they sufficiently fulfill the linear station model. If a station shows a significant derivation from linearity, e.g. after a seismic event, it is usually excluded from the set of datum points. The current best realization of a terrestrial reference system is ITRF2008 (see Figure 5.). For the celestial reference points astrometric and astrophysical stability criteria are considered, if available (Heinkelmann et al., 2007a). Since the number of observed radio sources is much larger than the number of available network stations, this set of datum points can be selected applying more stringent criteria. For the current conventional realization, the ICRF2 (see Figure 6.), besides the stability, the geometrical distribution of radio reference sources was considered as well (IERS, 2009). The metric of the VLBI baselines depends only on the inserted time scale and the speed of light, which is one of the most precisely known natural constants. The precise network scale of the terrestrial coordinates is truly a strength of the VLBI technique. If the time scales of the VLBI model are correctly handled in particular during the Lorentz transformation from barycentric coordinate time (TCB) to geocentric coordinate time (TCG), the resulting geocentric VLBI metric is one of the utmost accurate among the space geodetic techniques. The scale of space-geodetic techniques incorporating satellites, such as GNSS and SLR, additionally depends on the imperfections of Earth's gravity field models and the uncertainty of the geocentric gravitational constant GM. Those techniques are, however, needed for the realization of the geocenter, in particular SLR. While the satellite orbit configurations directly refer to the center of mass of the Earth system, VLBI is independent from those dynamics and thus it is not possible to refer to the center of mass with VLBI alone.

Figure 5. Kinematics of observatories of various space-geodetic techniques including VLBI (orange) as given by the ITRF2008 terrestrial reference frame solution determined at DGFI (http://www.dgfi.badw.de/), courtesy of M. Seitz

EOP are defined as the rotation parameters between the GCRS and the ITRS. VLBI provides a direct access to both systems. Thus, VLBI is the only technique for a direct determination of EOP. Satellite techniques require an additional transformation of their dynamic satellite orbit configurations to GCRS, liable to a number of error sources, and thus only derivatives of some of the EOP achieve a sufficient precision. Since five angles (EOP) are defined for a rotation, which could be achieved by only three independent angles, e.g. Euler angles, the EOP are by definition correlated with each other. Earth orientation parameters determined by VLBI have been used to determine a variety of quantities, such as the free core nutation (IERS Conventions, 2010) or ocean tidal terms (Englich et al., 2008).

Figure 6. Mean positional errors of the multi-session radio sources of ICRF2 observed by IVS. Larger positional errors (> 1000 μas) can almost only be found close to the galactic plane (the omega-shaped line). Figure is taken from IERS Tech. Note 35, courtesy of C. Jacobs

3.3. Atmospheric quantities

The main goal of atmospheric analyses is the determination of atmospheric water vapor. Atmospheric water vapor, e.g. described by precipitable water, can be obtained by multiplying a factor on the estimated zenith wet delays (Heinkelmann et al., 2007b). In principle, the neutrosphere parameters are optimally decorrelated at low elevations. If the elevation angle of the observation is too small, however, the scatter gets too large and the observation is likely to get lost. As a tradeoff, an elevation cutoff angle is applied, which is in the case of VLBI usually 5°. Small elevation cutoff angles are possible for VLBI, because VLBI antennae are directional antennae and there are no multi-path effects comparable to those present with non-directional e.g. GNSS antennae. Another criterion for optimal neutrosphere parameter determination is the spatio-temporal sampling. Since about the beginning of the 1990s, the

geodetic VLBI schedules require the antennae to point at very different directions within relative short time intervals. With such a spatio-temporal sampling the neutrosphere is observed with a good geometrical distribution within relative short time. Consequently, neutrosphere parameters can be successfully estimated with high temporal resolution.

Besides the standard analysis models and observation schedules, the precise determination of zenith wet delays depends on accurate surface air pressure values at the location of the network stations during the observation. The effects on the determination of zenith delays have been quantified and investigated. In particular the terrestrial reference frame, if not adjusted as well, can introduce large systematics into the zenith delay estimates. The weaknesses in the definition of the origin in z-direction of ITRF2000, for example, can cause apparent trends in atmospheric water vapor climatologies (Heinkelmann, 2008). In-situ measurements of air pressure have shown potential to be the best available data for this purpose. During the more than 30 years of observations, however, in-situ measurement time series of air pressure are often subject to inhomogeneities caused by a variety of possible effects. If those inhomogeneities are homogenized by appropriate procedures (Heinkelmann et al., 2005), the time series of zenith wet delay can be used to reliably estimate trends of atmospheric water vapor and other climate quantities. Besides, zenith wet delays can be used as a quality criterion for internal consistency (intra-technique comparison) and external validation (inter-technique comparison). Inter-technique comparisons with respect to other space-geodetic techniques at radio wavelengths have been carried out and published by a large number of authors. The neutrosphere delays determined by those techniques should equal each other in principle, if the reference points of the local instruments are situated at the same height. To adjust neutrosphere delays in terms of height a correction is necessary, which has to consider the height dependence of the symmetric neutrosphere model. Besides the aforementioned hydrostatic and non-hydrostatic (wet) zenith delays, also the mapping functions vary with height and contribute to the neutrospheric tie. The other type of neutrosphere parameter, the gradients should equal each other without a correction. In reality, however, neutrosphere parameters of various space-geodetic techniques differ (Teke et al., 2011), even if ties are applied. The reasons might be inherent simplifications of the neutrosphere model and neglections of cicumstances, e.g. the radomes above the instruments, which are not considered in the neutrosphere model. In addition, the wet zenith delay estimates, unfortunately, do not only describe the neutrosphere conditions, but also additional noise and systematics from unconsidered effects outside of the neutrosphere model, which show comparable elevation dependent characteristics.

The other examples of atmospheric quantities obtained by geodetic VLBI are less popular: Jin et al. (2008) showed that the hydrostatic component inside the total neutrosphere delay can be used to determine amplitudes of atmospheric tides and Tesmer et al. (2008) estimated coefficients of a model for atmospheric pressure loading deformations with an approach based on station height time series.

3.4. Further parameters obtained from group delays

Besides the aforementioned quantities, geodetic VLBI has shown its ability to precisely determine further parameters. These parameters are usually estimated by individually

optimized analyses designed for the specific purpose, while other parameters are not considered or constrained. Further parameters obtained by geodetic VLBI are

i.   Love and Shida numbers. Love and Shida numbers have been recently estimated by the IVS Analysis Center at the Insitute of Geodesy and Geophysics (IGG), TU Vienna, Austria (Spicakova et al., 2010). The values agree very well with the values reported in the IERS conventions (2004) and can be considered as an improvement over those values estimated by VLBI before (Haas & Schuh, 1996).

ii.   Eccentricities of network stations. For the determination of eccentricities the geodesist usually prefers a measurement, e.g. obtained by engineer surveying methods. Nevertheless, whenever such measurements are unavailable, it is possible to insert eccentricities into the parameter space. The largest eccentricities for geodetic VLBI antennae were measured at the mobile observatories roughly during the 1990s. If different equipment is installed at the same platform, the eccentricity at a site is likely to change between two mobile occupations. At stationary antennae large eccentricities are usually avoided. When precisely measured eccentricities are available, it is in principle possible to compare the measured ones with the estimated ones. The transformation from local measurement system into the geocentric Cartesian system of the apriori catalogue may, however, significantly degrade the precision of the measured eccentricity and thus the comparison.

iii.   The γ-parameter of the parameterized post-Newtonian theory. The γ-parameter describes how much unit mass deforms space-time and equals unity in Einstein's theory of gravity. For the γ-parameter determination, VLBI competes with ranging measurements to space crafts, which have nowadays shown to provide estimates with slightly better repeatability. Space-craft ranging measurements are, however, carried out at much smaller number of epochs and in almost one direction of the universe. VLBI, with its more than 30 years of continuous observations in quasi all directions of the universe, can in addition prove that this universal constant is indeed invariant to the measurement epoch and the directions in our universe. A review of the latest estimates and earlier VLBI results can be found in Heinkelmann & Schuh (2010).

iv.   Velocities of radio sources and other advanced astrometric parameters. Extra-galactic radio sources should in principle be subject to galactic rotation of about 5.4 μas per year (Kovalevsky, 2003). An exact determination of the size of this effect is, however, very difficult. One difficulty is the correlation with the precession rate, which is about 50 as per year. The models for precession are also adjusted using VLBI (Capitaine et al., 2003). In spite of the fact that galactic rotation takes place in the galactic plane and precession is defined along the celestial equator, galactic aberration may propagate into the precession rate estimated by VLBI (Malkin, 2011). Furthermore, the investigation of radio source velocities led Titov et al. (2011) to an estimate of the Hubble constant describing an anisotropic expansion of the universe or low frequency gravitational waves, and thus, cosmology has become an issue for geodetic and astrometric VLBI as well.

4. Analysis of ionosphere delays

The analysis of VLBI ionosphere delays presents an independent branch,

$$\tau_{iono} = \frac{1.34 \bullet 10^{-7}}{f_X^2} \left[mf_i(e_2)VTEC_2 - mf_i(e_1)VTEC_1 \right] + \tau_{offset,2} - \tau_{offset,1} \qquad (7)$$

enabling the determination of integrated electron density expressed by vertical total electron content *VTEC*. To derive *VTEC* from slant total electron content (STEC) the application of an ionosphere mapping function mf_i is required. Ionosphere mapping functions are e.g. specified by IERS Conventions (2010) and can have significant effects on the ionosphere parameters (Dettmering et al., 2011b). The total electron content is usually specified in TECU (1 TECU := 10^{16} electrons per m^2). The ionosphere delays are derived from the real observed frequency channels around the two center frequencies in X- and S-band (equation 5) and are stored together with their formal errors in IVS databases for correction of the group delay observable (see section 3). The difference is that for the group delay analysis ionosphere delays are applied as a correction, whereas for this approach they will be used as primary observations. A small part of the ionosphere delay analysis is in common with the group delay analysis: the geometry of the network stations and the radio source needs to be known. Ionosphere parameters are usually referred to geocentric systems, such as the conventional terrestrial system or the geomagnetic equatorial system. Thus, the position of the network stations and the radio source need to be known in a geocentric system at the epoch of each observation. After the radio source coordinates have been transformed, the geometry is given, e.g. through pairs of azimuth and elevation angles, in a geocentric system. The ionosphere delay describes the difference of ionization along the observed ray paths. In addition there is an unknown instrumental offset included for each network station $\tau_{offset,i}$. Each delay contains at least three unknowns. Thus, without additional assumptions it would not be possible to estimate ionosphere parameters. The first assumption is that instrumental offsets are constant during an observation session, i.e. over 24 h. In this case, it would be possible to determine parameters, if some observations could be projected onto the same parameter. If VTEC is estimated instead of STEC, it is possible to group the delays observed in various directions together within certain time intervals. Then, if the variation of the observations with time can be appropriately modeled, it is possible to reduce the number of unknowns. If short time spans are defined for the parameters, it is valid to assume that the ionosphere remains constant within these time spans. Since the maximum of ionization of Earth's ionosphere follows the movement of the Sun along the Earth's magnetic equator, this movement is accounted for in a simplified way

$$VTEC(t) = \left(1 + (\varphi' - \varphi) \begin{bmatrix} G_N \\ G_S \end{bmatrix} \right) VTEC \left[t + (\lambda' - \lambda)/15 \right] \qquad (8)$$

Where φ' and λ' are the latitude and longitude of the ionospheric pierce point and φ and λ are the latitude and longitude of the specific VLBI antenna. With this approach and the respective assumptions it is possible to obtain an over-determined problem wherein *VTEC(t)* with a

certain temporal resolution and instrumental offsets at each network station can be determined. Spatial asymmetry in north-south direction can be considered by parameterizing additional gradient parameters (G_N, G_S). This method for ionosphere parameter estimation was introduced by Hobiger et al. (2006) and applied in a slightly refined way by us (Dettmering et al., 2011b).

Comparing VTEC obtained by various space-geodetic techniques reveals small differences depending on the technique (Dettmering et al., 2011a). Among GNSS and VLBI the mean differences observed during the continuous observation campaign CONT08 are about 1 TECU, with a slightly larger formal error. Thus, no significant dispersive offsets were found. The result proves that the rather simple model assumptions provide results of acceptable quality.

5. The current and future role of VLBI

Geodetic and astrometric VLBI under the umbrella of the International VLBI Service for Geodesy and Astrometry (IVS) provided observations of very good quality in a consistent way since more than 30 years (Schlüter & Behrend, 2007). Since 1999 the IVS comprises an adequate platform for the work packages of geodetic VLBI, which need to be shared. Besides the international observation campaigns, various components of the work flow are carried out by different institutions, world-wide, what requires a certain amount of organization. The IVS organizes conferences, proceedings, technical and analysis workshops and schools and the procedures, which can be done in an operational way. IVS is a service of the International Association of Geodesy (IAG) and as such it contributes in a unique way to IAG's flagship, the Global Geodetic Observing System (GGOS). Part of VLBI's contribution to GGOS is given through its infrastructure. The infrastructure is usually expensive and immobile and thus, the installation of VLBI equipment is rather a long-term investment. For the determination of geodetic and astrometric reference frames this is on the one hand an advantage, because, once installed, VLBI observations are usually carried out for many years by the same equipment, but on the other hand a disadvantage, because the absolute number of geodetic VLBI antenna is too small for many geoscientific applications, which require higher spatial resolutions. VLBI is able to measure the longest baselines on Earth limited only by the necessary common view of extra-galactic radio sources. The satellite-based space-geodetic techniques are restricted for example by the common view of a satellite or rely on networks of satellites or stations and can only indirectly reach comparable distances. By VLBI the differences at very remote locations can be determined directly and thus it is a truly global and consistent measurement technique.

In general and through projects, such as the VLBI2010, the development of technique and in the following observational strategies, analysis procedures and software, will go on and will continue to improve geodetic VLBI. Besides the VLBI receiver improvements, the antenna development is an ongoing process. Within project VLBI2010 the antenna specifications for diameter have decreased to 10 to 12 m (Niell et al., 2005; Shield & Godwin, 2006). The lower requirements for antenna diameters are possible because other receiver components, such as the effective bandwidth or the data recording rate, got significantly improved in recent years.

Several countries already have built or plan to build VLBI2010 compatible new VLBI tele-scopes, e.g. Australia, Spain, and Germany. The number of individual members in the IVS increases and we are looking faithfully into future.

In face of the upcoming GAIA optical astrometry mission (GAIA stands for global astrometric interferometer for astrophysics), VLBI will be needed to link the GAIA astrometry catalogue via the radio sources with Earth. The GAIA mission will operate only a limited number of years; five years are foreseen by now. The extrapolations of star positions of the GAIA catalogue outside of the temporal measurement range of its mission still foresee very high precision, but VLBI observations will go on in future and thus it will be possible to maintain VLBI based frames long after the GAIA mission will have ended.

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