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Geodetic Analysis Overview

Harald Schuh

Institut für Geodäsie und Geophysik, Techn. Univ. Wien
e-mail: `hschuh@luna.tuwien.ac.at`

Abstract

For the VLBI data analysis the best presently available knowledge is used to mathematically recreate, as closely as possible, the situation at the time of observation. The goal is to determine precise values of the parameters geodesists, geophysicists and astronomers are interested in, e.g. baseline components, radio source positions or Earth orientation parameters. A general overview about data analysis of geodetic/astrometric VLBI experiments is given. The procedure of data analysis is explained and the geophysical, environmental and instrumental effects which have to be taken into account are presented. A sample of the most interesting results is presented.

1. Introduction

The geodetic and geophysical interest in VLBI is based on the use of an inertial reference frame formed by a given set of extremely compact extragalactic radio sources. VLBI measures very accurately the angles between the Earth-fixed baseline vectors and the space-fixed radio sources. Thus, even the most subtle changes in the baseline lengths and in the angles between the reference systems can be detected. The main geodynamical phenomena such as polar motion, UT1 variations, nutation and precession, Earth tides, ocean tidal response, and tectonic plate motions can be monitored with unprecedented accuracy.

The research fields that profit most from the geometric potential of VLBI are those dealing with the motions of the celestial bodies, in particular the Earth-Moon system, and the orientation and the size of the Earth itself: astrometry and geodesy. These fields are usually meant to imply a much broader area, namely fundamental astronomy and geosciences, such as geophysics, meteorology and oceanography. The topic of gravitational light deflection is also intimately related to all of these fields, because it forms part of the fundamental space-time model describing the physical reality of VLBI. A comprehensive overview about the fundamentals of geodetic/astronomic VLBI is given by Schuh and Campbell (1994).

2. Analysis of High Precision Interferometry Observations

The term high precision interferometry is used here to include all those applications of VLBI that rely on the exploitation of the group delay observable τ. It is this quantity which allows to determine the "macroscopic" geometry of the interferometer, i.e. the baseline-source geometry that relates the location of the radio telescopes on the revolving Earth to the infinitely distant compact radio sources. These pointlike emitters without proper motion are ideally suited to serve as fixed beacons in the heavens, allowing to monitor even the smallest departures from the computed motions of the receiving stations.

The VLBI data analysis model is developed using the best presently available knowledge to mathematically recreate, as closely as possible, the situation at the time of observation. Then either a least-squares parameter estimation algorithm, a Kalman filter or other estimation methods are used to determine the best values of the quantities to be solved for. Before this process starts, the raw observations have to be cleaned from several systematic effects, which in fact limit the final accuracy of the results. The flow diagram of a geodetic VLBI data analysis is shown in Figure 1.

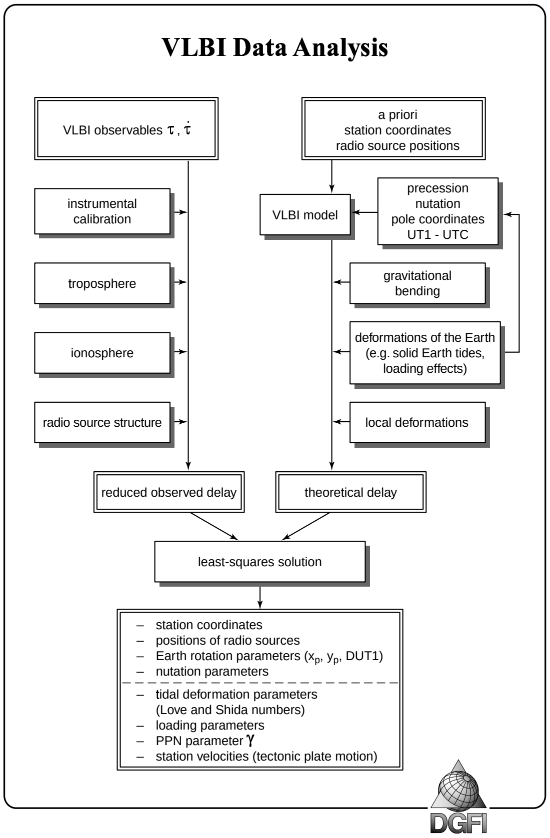
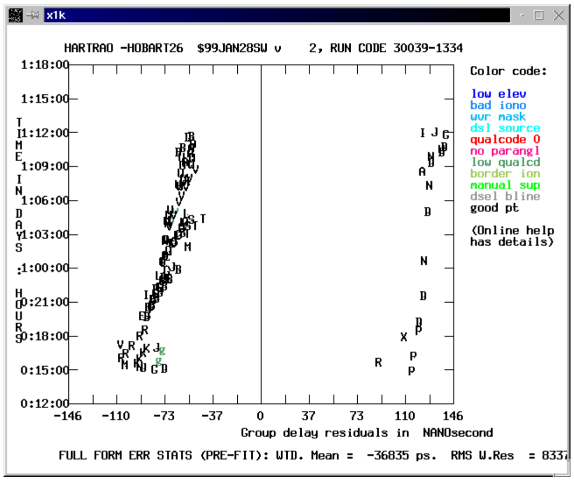


Figure 1. Flow diagram of a geodetic VLBI data analysis.

The system can be seen to have two main streams, one containing the actual observations which undergo instrumental and environmental corrections, and the other to produce the "theoreticals", beginning with the "a-prioris", a set of starting values for the parameters of the VLBI model. Both streams converge at the entrance to the parameter estimation algorithm, e.g. the least-squares fit, where the "observed minus computed" are formed. The instrumental effects include systematic clock instabilities, electronic delays in cables and circuitry and the group delay ambiguities. The latter are due to observation by a multichannel frequency setup covering the total spanned bandwidth around the X-band frequency of 8.4 GHz and the S-band frequency of 2.3 GHz. The group delay ambiguities can be made visible (see Figure 2) and removed by the analyst when for a first solution only the group delay rates $\dot{\tau}$ are used but the group delay residuals are plotted, too. As the group delay ambiguity spacing is well-known, e.g. 50 nsec, 100 nsec or 200 nsec, the analyst can select one level on which all residuals – and thus the corresponding group delay observables – are shifted. Care has to be taken that the group delay closure within each triangle of the multistation VLBI network is zero.

The instrumental delay changes are monitored by the phase and delay calibration system which is part of the MkIII system and the MkIV system. Figure 3 shows the cable calibration data recorded and entered into the station log file at the station Fortaleza, Brasil. At the beginning and the end of the VLBI session the cable sign check readings are done that allow the determination of the sign which is needed when applying the cable calibration correction to the observables. It happens frequently that the station log files contain wrong entries (outliers, offsets, gaps, ...) which have to be edited manually by the analyst.

At the telescope the distance between the feed horn and the axis intersection, which constitutes the baseline reference point, is assumed to be constant at the mm level. In this case it becomes part of the clock offset parameter which will be described later in this section. An axis offset model is applied to each antenna where the pointing axes do not intersect. Large telescopes such as the Effelsberg 100-m antenna exhibit elevation dependent changes in the focal distance which can however be modeled to a level of a few millimeters (Rius et al., 1987).



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FULL FORM ERR STATS (PRE-FIT): WTD. Mean =  -36835 ps.  RMS W.Res  = 8337
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Figure 2. Group delay residuals of a first "delay rate only" solution spaced by the group delay ambiguities of 200 nsec (S-band, standard MkIII frequency setup).

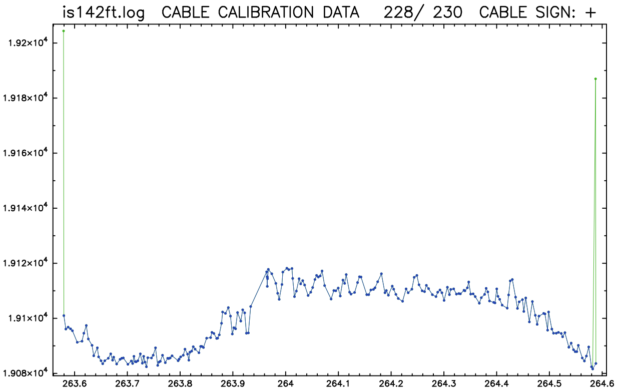


Figure 3. Cable calibration data recorded at Fortaleza, Brasil, with cable sign check readings at the beginning and the end of the session.

The effect of the atmosphere on VLBI observations is still considered to be the most serious problem, because at widely separated stations the elevation angles of the telescopes pointing to the same source differ greatly as well as the meteorological conditions themselves. The neutral atmosphere, essentially the troposphere, presents similar problems in VLBI as in GPS observations. Its influence on radio signals adds up to an extra zenith path of 1.8 to 2.5 meters. The contribution of the dry part is rather stable, although special care has to be taken to choose a proper mapping function (Davis, 1985; Niell, 1996) for the elevation angles lower than 20°. The wet component, although the smaller part of the total tropospheric effect, changes rapidly and can also be monitored by some means. The most promising – albeit costly – method appears to be the water vapor radiometer (WVR) technique, which consists of measuring the microwave thermal emission from water vapor near 22 GHz in the line-of-sight (Elgered et al., 1982; Emardson et al., 1999).

The ionosphere, which is a highly dispersive medium in the radio frequency band, can be dealt with to first order by using two different observing frequencies. In geodetic VLBI the frequency pair of $f_S = 2.3$ GHz (S-band) and $f_X = 8.4$ GHz (X-band) is used throughout. The ionospheric group delay corrections for the X-band observations are computed from the differences of group delay measurements at X-band and S-band:

$$\Delta\tau_x^{ion} = (\tau_x - \tau_s) f_s^2 / (f_x^2 - f_s^2) \qquad (1)$$

In contrast to GPS, where a very close frequency pair has been chosen, in VLBI the factor to convert the difference into a correction for the higher band is very small: 0.081, so that there is no appreciable error contribution from the S-band observations.

A major problem is constituted by the fact that most of the observed "compact" radio sources tend to show structure at the level of a few mas. These effects, in particular the changes in the structure, pose a limit on the accuracy of the radio reference frame. Permanent monitoring of the structure, which is also accomplished by analysing VLBI data, can be done in parallel to the geodetic analysis, thus providing a means to correct for the structure effects (Schalinski et al., 1988; Campbell et al., 1988; Charlot, 1993; Zeppenfeld, 1993; Charlot and Fey, 1999).

Now let us turn to the model side of the geodetic VLBI analysis. The geometric time delay of signals arriving at the two radio telescopes is to first order a function of the baseline vector **b** between the two telescopes and of the unit vector **k** in the direction of the radio source:

$$\tau(t) = -\,\boldsymbol{b}' \cdot \boldsymbol{k}(t)/c \tag{2}$$

where

$$\boldsymbol{b}' \cdot \boldsymbol{k}(t) = b_x \cos\delta \cos h(t) + b_y \cos\delta \sin h(t) + b_z sin\delta \quad , \tag{3}$$

with the geocentric baseline components b_x, b_y, b_z, the radio source positions α, δ and the Greenwich hour angle $h(t)$ of the source $h(t) = GST - \alpha$ (GST - Greenwich sidereal time). The negative sign reflects the conventions used in defining τ and **b**. c is the velocity of light.

The fundamental geometric model of the time delay τ_g forms the heart of the system. This model has evolved from its basic form in a geocentric system [equation (2)] to the fairly complex relativistic formulation referred to the solar system barycenter (SSB). Initially the basic model of equation (2) was extended by the so-called retarded baseline effect, which accounts for the finite travel time of the signals between reception at the two telescopes on the revolving Earth. In spherical astronomy this effect is known as diurnal aberration and in fact it turns out that to first order the application of the retarded baseline effect is equivalent to correcting the source vector **k** at station 2 for diurnal aberration.

The relativistic formulation includes both the effects of special relativity (SRT) and of general relativity (GRT), but for reasons of practicality these are treated separately and added together on the level of the time delay (Preuss and Campbell, 1992; Schuh and Campbell, 1994):

$$\tau_g = \tau(SRT) + \tau(GRT) \tag{4}$$

The effects of special relativity to compute $\tau(SRT)$ arise from the fact that quantities defined in coordinate frames moving relative to each other have to be related by transformations of the Lorentz type with v/c^2 as the characteristic quantity in the time delay correction terms. The choice of two particular coordinate systems (the celestial system referred to the SSB and the terrestrial system referred to the geocenter) used to describe the VLBI model arises from practical considerations: the motions of bodies in the solar system and the positions of the radio sources are most readily defined in a celestial system, while the actual baselines between the telescopes are usually required in a terrestrial system. The velocity of the geocenter with respect to the SSB ($\sim$ 30 km/sec) and the velocity of station 2 with respect to the geocenter ($<$ 0.46 km/sec) are entered. In the geometric VLBI model these velocities have to be computed with an accuracy of better than 10^{-6}. The equation for $\tau(SRT)$ accounts also for the difference in SSB coordinate time and the geocentric proper time as well as for the fact that the station clocks are located at fixed points on the Earth's crust. In Oct. 1990 a workshop was held at U.S. Naval Observatory to bring the VLBI model builders (mostly theoretical relativists) and the model users (mostly geodesists with little experience in relativity) together. As an output of this workshop a so-called *consensus model* to guarantee picosecond delay accuracy was obtained for the geodetic VLBI observables (Eubanks (ed.), 1991).

The effect of gravity on the propagation of electromagnetic waves (GRT) is no less important. According to GRT, space-time is deformed by the presence of masses. $\tau(GRT)$ is computed as a sum of the influences of all gravitating bodies which are close to the signal path in particular the Sun and the Earth itself. Thus, the Schwarzschild radii of the Sun and the Earth are needed and the vectors from these bodies to the VLBI antennas. The most massive object in our vicinity is of course the Sun, which accounts for more than 99% of the total effect. Even at an angle of 90° away from the Sun the differential delay effect (GRT) for a 6000 km baseline is still 0.56 nsec (Table 1). For the other bodies of the solar system the corresponding Schwarzschild radii have to be used, if necessary, i.e. if the radiation from the observed radio source passes close to that body. At the present level of accuracy of VLBI the major planets also contribute a bending effect which cannot be entirely neglected. If Jupiter arrives within less than 1° of an observed source, its influence on ray bending has to be taken into account as can be seen from Table 1. Another small but significant contribution (< 20 psec) comes from the gravity field of the Earth itself. If neglected, this effect shows up as a scaling error in the geodetic results.

Θ (Sun) [°]	τ^{s}_{grav} [ns]	Θ (Jupiter)[°]	τ^{J}_{grav} [ns]
0.267	169.52	Rim	1.582
1	45.30	0.017 ($\widehat{=}$ 1')	0.605
5	9.06	0.167 ($\widehat{=}$ 10')	0.062
10	4.54	0.5	0.021
30	1.53	1	0.010
60	0.79	5	0.002
90	0.56	10	0.001
120	0.46		
150	0.41		
180	0.40		

Table 1: Gravitational path delay as a function of spherical distance from the Sun and Jupiter. Given are maximum values for a 6000 km baseline (Schuh, 1987).

As already mentioned above the baseline vector ***b*** is normally expressed in a terrestrial three-dimensional cartesian coordinate frame defined by a number of VLBI radio telescopes, while the radio source positions are given in a quasi-inertial celestial reference frame in space. In order to express ***b*** and ***k*** in the same coordinate system, several transformations are necessary. These can be applied to either vector. Equation (2) can be written as:

$$\tau = -\frac{1}{c}\,\boldsymbol{b}'\mathbf{WSNP}\,\boldsymbol{k} \tag{5}$$

where ***W*** is the rotation matrix for polar motion (wobble), ***S*** is the diurnal spin matrix, ***N*** is the nutation matrix and ***P*** is the precession matrix.

The description of the Earth's orientation with respect to the celestial system (precession, nutation), the motion of the Earth's axis with respect to the crust (polar motion) and the phase angle of the Earth's rotation (expressed by UT1-UTC) have to reach the same level of accuracy as all the other model components, which means roughly 0.0001 arcsec (0.1 milliarcsecond). Models are used to calculate a priori the periodic variations of the Earth rotation parameters (ERPs) due to the Earth tides (e.g. Yoder et al., 1972; Tamura, 1993) and due to the ocean tides (e.g. Brosche et al., 1989; Wünsch and Seiler, 1992; Ray et al., 1994).

The parameters in equation (5) or combinations of parameters can be determined from VLBI experiments depending on the configuration of the network and the objectives of the session. The precision of the Earth rotation parameters observed by VLBI is to first order proportional to the baseline lengths of the network. Thus, only measurements carried out in large networks, i.e. with baselines longer than 6000 km, are used for the determination of the Earth's orientation. Present VLBI networks observe up to 25 radio sources several times in a predetermined sequence during a period of 24 hours providing 1000 to 2000 individual delay observables τ. Today, the formal error of the pole position determined in a standard 24-hour observing session lies in the range of about 0.1 to 0.2 milliseconds of arc (mas).

Another important factor is the geometry of the VLBI network. Long east-west baselines are mainly sensitive to UT1 whereas networks with long north-south components allow to measure precisely both components of the pole position. The sensitivity can be derived from the influence on the delay observable:

$$\Delta\tau_{xp} = \frac{\partial\tau}{\partial x_p}\Delta x_p, \tag{6}$$

$$\Delta\tau_{yp} = \frac{\partial\tau}{\partial y_p}\Delta y_p. \tag{7}$$

where Δx_p, Δy_p are the changes in the pole components and Δx_p, Δy_p are the respective changes in the delay observable. The partial derivatives $\partial\tau/\partial x_p$, $\partial\tau/\partial y_p$ are dependent on the baseline components b_x, b_y, b_z, the declination δ_s and the Greenwich hour angle h_s of the radio source:

$$\frac{\partial\tau}{\partial x_p} = -\frac{1}{c}\left[(b_x \sin\delta_s - b_z \cos\delta_s \cos h_s)\right], \tag{8}$$

$$\frac{\partial\tau}{\partial y_p} = -\frac{1}{c}\left[(b_y \sin\delta_s - b_z \cos\delta_s \sin h_s)\right], \tag{9}$$

For instance, the baseline between the Wettzell Geodetic Fundamentalstation (Germany) and the Hartebeesthoek Radio Astronomy Observatory (South Africa) whose z component of 7580 km is about eight times its x component and five times its y component, yields large values for the partial derivatives with strong variations due to the multiplication by $(\sin h_s)$ or $(\cos h_s)$. Thus, this baseline provides high sensitivity for changes in both components of polar motion.

Periodic and aperiodic deformations of the Earth's crust have to be taken into account as well. Solid Earth tides show diurnal and semidiurnal oscillations which cause vertical deformations in a range of ± 20 cm and horizontal displacements of about 30% of the vertical effect (e.g. Mathews et al., 1997). More difficult to model is the loading by the water masses of ocean tides and currents (ocean loading), which amounts to as much as a decimeter on some coastal or island sites (Scherneck, 1991). The loading effects due to air pressure variations (atmospheric loading) also reach the level of significance in VLBI modeling (Rabbel and Schuh, 1986; Haas el al., 1997).

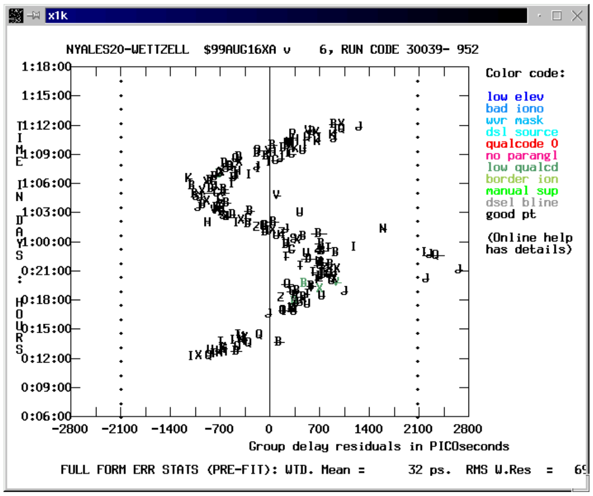
Finally, deformations of the telescope structure which occur during the 24 hours of an observing session or between the observing sessions have to be taken into account. They can be caused by thermal expansion of the telescopes or snow and ice loading of the antenna (Haas et al., 1999).

The so-computed *theoretical delays* are then compared with the *reduced observed delays* by a parameter estimation process, e.g. a least-squares fit. The parameters which are estimated belong to different groups:

1. Auxiliary parameters which have to be computed but are usually not interesting for the geodesists, e.g. clock parameters and atmospheric parameters.

2. Geodetic/astrometric parameters which are of interest for the user community, e.g. baseline components or station coordinates with respect to a reference station, Earth orientation parameters (UT1-UTC, pole coordinates, nutation coefficients) or radio source positions.

Let's start with the auxiliary parameters. As a clock model usually second order polynomials are entered and occasional clock breaks have to be introduced. Clock modeling is still very much an interactive procedure and belongs to the editing session. In present standard VLBI solutions the clock estimation algorithm is designed to model short-term, random clock variations while enforcing realistic physical constraints on continuity and rates of change. When all clocks are "well behaved" a typical algorithm which is applied is as follows: the clock at one site is designated the reference clock and the differences between this clock and the other site clocks are modeled. These differences are modeled as the sum of two functions: a second order polynomial and a continuous, piecewise-linear function with an initial value of zero. The three coefficients of the polynomial correspond to clock epoch offset, clock frequency offset, and clock frequency drift. They are unconstrained in the solution because these parameters can be of any size for real hydrogen masers. In the piecewise-linear function, the offset at the end of each linear segment is estimated. In the solutions done by the NASA/GSFC VLBI group, the linear segments are only one hour long each (Ryan et al., 1993) whereas European VLBI experts usually choose longer segments, e.g. four or six hours (Nothnagel and Campbell, 1993). Residuals for the group delay observables on the baseline Ny Ålesund-Wettzell of a first solution with a simple clock model are plotted in figure 4. Figure 5 shows the clock of Wettzell station modeled by a piecewise-linear function as described above clearly corresponding to the behavior of the residuals.



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NYALES20-WETTZELL  $99AUG16XA v    6, RUN CODE 30039- 952
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Figure 4. Group delay residuals of a first solution with a simple clock model for Wettzell station. Time axis is from bottom to top.

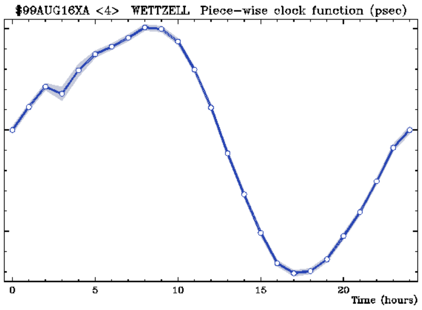

Figure 5. Clock of Wettzell station modeled by a piecewise-linear function as described above. Time axis is from left to right.

There are also different strategies for modeling the influences of the troposphere on the radio signals. Some of the VLBI analysis groups solve for tropospheric wet delay corrections only, some others for total zenith delay corrections, again approximated by a piecewise-linear function. Also so-called gradients are determined to take into account azimuthal dependencies (Davis et al., 1993).

Now, we continue with those parameters which are the subject of geodetic and astrometric VLBI observations. In geodetic VLBI data processing there are two levels of least-squares solutions, one in which only the "local" unknowns are estimated from a single session (such as clock and atmospheric parameters for the participating stations as described above, Earth orientation parameters UT1-UTC, components of polar motion x_p, y_p, and nutation parameters in longitude and in obliquity) thus creating a first data base version of each particular experiment, and another which collects a considerable number of available experiments covering a long time base for a combined solution including the "global" unknowns such as station and source positions and further geodynamical and astronomical parameters.

The latter can be parameters of a model for the solid Earth tides where the relevant parameters, i.e. the Love and Shida numbers, can be estimated (Mitrovica et al., 1994; Schuh and Haas, 1998). Deformation due to ocean loading is a small second order effect but large enough to be revealed by detailed analyses of VLBI measurements (Schuh and Möhlmann, 1989). Ocean loading parameters could be successfully determined from VLBI, e.g. by Sovers (1994) and by Haas and Schuh (1998). The loading effects due to air pressure variations (atmospheric loading) were also investigated based on VLBI measurements and relevant parameters were determined from VLBI (Haas et al. 1997).

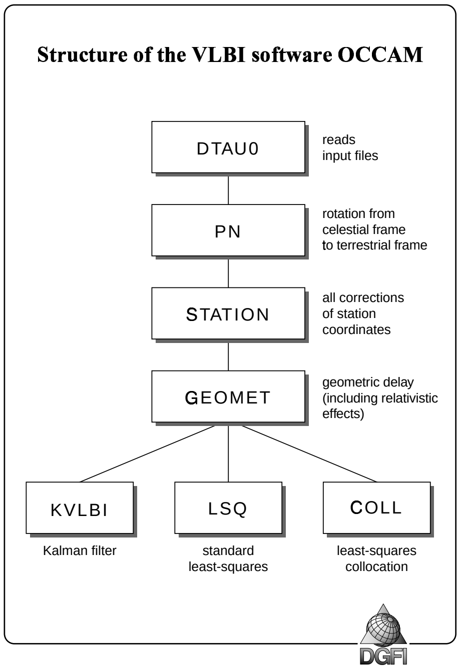

Figure 6. Flow chart of OCCAM.

Since the early 80's VLBI observations have been used extensively to verify Einstein's theory in its Parameterized Post Newtonian formulation (PPN). Two approaches have been used, one designing special experiments to observe sources such as 3C279 and 3C273 during their close approach to the Sun and the other using all available data from routine geodetic experiments to achieve the accuracy by the sheer number of the observations. The γ-factor, which in the Einstein theory should be equal to unity, has been found to show no significant departure from this value to the level of 0.1% (Carter et al., 1985). More recently, this accuracy level has been further improved to 0.02% (Robertson et al., 1991). Attempts have also been made to verify the gravitational bending near Jupiter (Schuh et al., 1988), but the effect is only marginally significant (< 100 psec) at very close encouters, i.e. less than a few arcmin (Campbell, 1989; Treuhaft and Lowe, 1991).

The theory of plate tectonics, which stipulates that the Earth's crust is formed by a mosaic of separate major plates that are in motion relative to each other, has now been universally accepted. Predictions derived from geophysical evidence yield motions of a few centimeters per year. With the large global VLBI data sets including now almost two decades of regular observations, parameterised plate models have been successfully determined based on VLBI solutions (e.g. Ryan et al., 1993).

In view of the extremely high precision inherent to VLBI, the modeling accuracy has to be brought down to better than a few millimeters on the global scale. Great efforts have been made to develop comprehensive geodetic VLBI data analysis software systems, which include all aspects of the multi-faceted reality of VLBI. Among the various VLBI software systems the MkIII Data Analysis System is probably the most prominent one. It is built around the CALC/SOLVE software system developed jointly by the US East Coast VLBI groups. At present CALC version 9.1 is used. This software has become a sort of standard against which the other systems can be compared. Other software systems at the same level of accuracy are the OCCAM package (see fig. 6) developed by European VLBI groups in Bonn, Madrid and Saint Petersburg (Schuh, 1987, Zarraoa et al., 1993; Titov and Zarraoa, 1997) and the MASTERFIT/MODEST software developed at Jet Propulsion Laboratory, Pasadena (Sovers, 1991; Sovers et al., 1998).

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