International VLBI Service for Geodesy and Astrometry

Working Group 3

VLBI2010

Report of the Subgroup on Data Analysis

(12.05.2004)

Chair

Harald Schuh (HS)

Members

Johannes Boehm (JB)
Sergei Bolotin (SB)
Roger Capallo (RC)
Gunnar Elgered (GEl)
Gerald Engelhardt (GEn)
Rüdiger Haas (RH)
Hideo Hanada (HH)
Thomas Hobiger (TH)
Ryuichi Ichikawa (RI)
Sergei Klioner (SK)
Chopo Ma (CM)
Dan MacMillan (DM)
Zinovy Malkin (ZM)
Shigeru Matsuzaka (SM)
Arthur Niell (ANi)
Axel Nothnagel (AN)
Wolfgang Schwegmann (WS)
Ojars Sovers (OS)
Volker Tesmer (VT)
Oleg Titov (OT)

1. Geodetic and Astrometric Data Analysis

1.1 Data analysis: improved models

1.1.1 Loading corrections

Currently it is possible to calculate mass loading corrections for atmospheric pressure loading, hydrology loading, tidal and non-tidal ocean loading. For instance the atmospheric pressure loading corrections derived from National Center for Environmental Prediction (NCEP) data assimilation pressure fields every 6 hours are already being applied in standard analyses of several IVS Analysis Centers. Petrov and Boy (2003) describe the algorithm used and the validation of the model. Atmospheric loading corrections are also calculated by Hans-Georg Scherneck based on ECMWF data and are available for download from http://www.oso.chalmers.se/~apload.html. These are used routinely for example in the analysis of the European geodetic VLBI sessions (Haas et al. 2003a). There is also the IERS Special Bureau for loading which is supposed to release atmospheric loading corrections on a global scale. This question is not easy to be answered, since the atmospheric pressure loading effects cannot be simply expressed as being proportional to the deviation of the local pressure from some reference pressure, but large scale effects have to be considered. It has to be mentioned here that the question of the reference pressure, i.e. to which pressure the atmospheric loading corrections should be referred has to be answered by all space geodetic techniques and waits for a treatment by the related IAG Working Group 1.2.1 'Datum Definition of Global Terrestrial Reference Frames'. A possible definition of a reference pressure at a station would be to take a global mean pressure at sea level and add the influence of the station height using a simple formula.

Hydrology models generally suffer from a lack of sufficient input global measurement data. Anyway, the models are getting better (e.g., Milly et al., 2002) and application of these models does explain part of the seasonal signal in VLBI observations. When better hydrology models are developed in the future, the hydrology loading computations can be updated. Deformation due to snow loading can reach up to 3-4 mm and has to be treated separately (e.g., Schuh et al., 2004). The importance of local hydrological effects on space geodetic measurements have recently been demonstrated e.g., by Tobita et al. (2004) and Munekane et al. (2004).

Currently, ocean tide loading is computed from ocean tide models based on TOPEX/Poseidon altimeter sea-surface height measurements and hydrodynamic finite elements models (e.g., Scherneck et al., 2002) The recent models explain more of the observed site displacement at tidal frequencies than the earlier models. In the future, it would be desirable to develop more refined ocean models for regions near some VLBI stations to improve ocean tide loading estimates. Non-tidal ocean loading is a small effect (~1-2 mm peak-to-peak) and there are several current ocean models that can be used to compute the loading.

1.1.2 Antenna deformation

Two approaches to account for the effect of thermal deformation of antennas are (1) directly measuring the height variations of the antenna and (2) model the height variations using the antenna dimensions, antenna material expansion coefficients, and measured temperatures (Nothnagel et al., 1995; Haas et al., 1998; IERS Conventions 2003). The VLBI telescopes at Onsala and Wettzell are equipped with invar rod or invar wire measurement systems that monitor the local height variations of the telescope foundations. These invar systems would be ideal, but if an antenna is not equipped with such a system, then the thermal expansion should be modeled based on measured environmental temperatures. For most VLBI antennas, the actual antenna structure temperature is not available so that the surrounding air temperature has to be used. This is a problem because there is a delay time between changes in air temperature and the structure temperature. Scherneck et al. (2002) show that at Onsala and Wettzell, using the mean daily outside temperature yields corrections that agree on the level of better than 1 mm with the invar measurements. Haas et al. (2003b) demonstrate that a more advanced modeling of thermal deformation based on environmental temperature agrees on the level of 0.1 mm with actually height variations measured by the invar rod system at Onsala. If global geodetic VLBI wants to reach the millimeter level till 2010 all stations should establish similar height monitoring systems and temperatures should be measured at several points of the antenna surface. Appropriate modeling requires the definition of a reference temperature, preferably in agreement with the other space geodetic techniques as their instruments or pillars might also be subject to thermal expansion. Besides thermal deformation, also gravitational deformations of the telescope structures and their impact on the geodetic VLBI observations have to be studied and if necessary appropriate correction models have to be developed. Finite element models for telescope structures appear to be a plausible approach for these effects (Clark and Thomson, 1988).

1.1.3 Implementation of the IAU Resolutions 2000 and the IERS Conventions 2003

The implementation of the new TRF-to-CRF transformations in CALC is nearly complete. Transformations using both the new paradigm (CEO based, non-rotating origin method) and the classical model (equinox-based, IAU2000A precession-nutation) have been coded up, along with their time derivatives and partial derivatives with respect to UT1, x/y polar motion, X/Y nutation (CEO based), and $\Delta\psi/\Delta\varepsilon$ (equinox-based). The theoretical model will use the CEO based transformations, and a correction will be computed for the difference between the two transformations. Modifications of CALC for other parts of the IERS Conventions 2003 (local displacements, the relativity model, etc.) are just now going to be started.

The situation for the other VLBI software packages such as OCCAM, Steelbreeze, and GLORIA is quite similar: the full implementation of the new IERS Conventions 2003 including the IAU Resolutions 2000 has already started but validation and full testing will take another one or two years. Concerning common VLBI conventions also IVS Analysis Conventions should be defined covering all effects which are unique to VLBI and are not contained in the IERS Conventions.

1.1.4 Source structure effects

Most of the sources that are observed have structure that has characteristics of a core-jet morphology. Fey and Charlot (1997) have developed a source structure index that increases with the level of source structure complexity. They have examined the complexity of sources that are used in geodetic observing and found that a large fraction of the ICRF sources have significant source structure. Sovers et al. (2002) used source maps generated from RDV VLBI sessions to calculate source structure corrections. Source coordinate scatter was reduced by 4-8 microarcsec. Structure correction contributed about 8 psec of residual delay to a typical session wrms residual delay of 30 psec. In the future, it will be desirable to make source maps so that source structure corrections can be applied routinely. This can certainly be done for sources observed in the RDV sessions; it is possible that adequate maps could be derived from some non-RDV standard geodetic sessions. If the application of source structure corrections to the observed group delays (or phase delays) has shown to improve the geodetic results in terms of wqrms or baseline repeatability, a kind of 'service' seems to be required that provides the source structure maps and if possible also the source structure corrections to the IVS Analysis Centers.Taking into account the tendency to move geodetic VLBI observations to higher frequencies, thorough investigations should be performed to estimate the systematic differences in radio source positions in various frequency bands.

1.1.5 Improved variance-covariance modeling of VLBI observations

In contrast to the functional representation of the geometric-physical properties of VLBI observations, the stochastic properties (e.g., due to functionally not ascertainable influences) have not been handled with much care so far. Recently, variance and covariance components were estimated from a large data set of VLBI observations between 1984 and 2001. It was found that the variance-covariance matrices which are usually used in VLBI data analysis have deficits in station and elevation dependent attributes. These deficits can be overcome by refining the corresponding variances. This analysis also made clear that in todays' VLBI solutions, correlations between observations can be neglected in most cases: the largest correlation coefficients were detected as due to the correlation process (estimated average from approx. 2200 sessions: 0.2, see Tesmer (2003)). Nevertheless there can be stronger correlations between observations of some particular sessions, probably due to deficits of the functional model. As estimated variance components depend on the applied functional model, the respective mapping function (like for example IMF or VMF instead of NMF) can affect the elevation dependence of variances of VLBI observations.

Tests were carried out concerning the repeatability of estimated station positions as well as tests of the similarity of EOP, determined from simultaneous NEOS-A and CORE-A sessions. They lead to the conclusion, that present-day VLBI solutions (using the NMF as mapping function) can be improved when station and elevation dependent refinements of the variances of the VLBI observables are used (Tesmer and Kutterer, 2004). Therefore, indirect effects of the refined stochastic properties on the estimated parameters have to be investigated, too, including (1) readjusting the weights of the constraints for the auxiliary tropospheric and clock parameters, (2) readjusting the criterion for outlier tests as well as (3) readjusting the chosen elevation cutoff angle.

Least squares collocation technique e.g., realized as an option within OCCAM, permits to calculate the correlations between observables. The covariance functions of stochastic parameters (clock offset, troposphere) are used to develop a more advanced adjustment procedure. It was shown by Titov and Schuh (2000) for one sample session that time dependent correlation coefficients for selected baselines can reach 0.5 and baseline-dependent correlation coefficients (for the same epoch and one common station) can reach 0.74. Such large values can be caused by site-dependent sources of errors that expand through all corresponding baselines.

1.2 Data analysis: new strategies

1.2.1 Robust and Reliable VLBI Solutions

VLBI solutions are carried out on the basis of least-squares adjustments, collocation, Kalman filtering, or SRIF (Square Root Information Filter). In all cases station clock and atmospheric refraction parameters have to be estimated as auxiliary parameters together with the geometric parameters, i.e. station coordinates, Earth orientation parameters (EOP) and radio source positions. From a single session normally only EOP and/or station coordinates are estimated together with the auxiliary parameters. In recent years refined modeling of the auxiliary parameters has lead to an increase in the number of parameters estimated and constraints are introduced to a much larger extent than earlier on. This development resulted in a loss of robustness of the solution with the consequence that the numerical results vary rather strongly depending on individual delay observables excluded from or included in the adjustment process. When speaking about robustness of the VLBI data this also means that hardware problems at the stations should be reduced which for instance require the estimation of baseline clock parameters in the data analysis. Robustness and reliability of VLBI solutions are key elements of the quality of VLBI results. Therefore, improved analysis strategies together with observation scheduling will have to be developed which reduce the influence of single observations on the results.

1.2.2 Consistency of TRF, EOP, and CRF

Currently there are several different levels of consistency issues in VLBI data analysis: a) between TRF, polar motion and UT1, b) between CRF, UT1 and celestial pole offset, and c) throughout TRF, EOP and CRF. While a) is generally no problem in the estimating process and consistent parameters can easily be conveyed via SINEX files, the other two items are less straight forward because of the CRF determination involved. So far, the best realization of a CRF, the ICRF (Ma et al., 1998) with its extensions, was generated in a very special solution setup. The reason for this was that any incorrect modeling of station drifts would inflict systematic effects on the positions of some of the radio sources. Therefore, station coordinates had been treated as time series parameters in the solution for the ICRF and its extensions. Since so far the ‘official’ IVS products are not obtained by a rigorous solution from a single simultaneous multi-purpose estimation process of all parameters including station positions, separate solution types still have to be set up depending on their purposes.

An important goal for 2010 is the generation of consistent VLBI multi-purpose solutions for TRF, EOP, and CRF (‘VLBI complete solutions’). For this, investigations have to be started on the propagation of systematic effects between reference frames in VLBI complete solutions.

The consistency of the VLBI products is of particular importance with respect to its contribution to the IERS and to the new IAG project IGGOS (Integrated Global Geodetic Observing System). As the main idea of IGGOS is the integration of various space geodetic techniques regular precise surveys of the local ties at stations with more than one technique are required, too.

1.2.3 Intra-VLBI combinations of complete solutions

The generation of VLBI complete solutions will offer unique opportunities of combinations which are rigorous to the utmost extent. While combination tools on the basis of datum-free normal equations in SINEX format are currently being developed at various institutions their use is still restricted to subsets of the geometry parameters. When VLBI complete solutions will be available on a routine basis combinations will be carried out on a session by session basis as well as on the basis of solutions with complete VLBI data sets (global solutions). These can be used for the combination on the next level, i.e. between the various space techniques by the IERS and/or within IGGOS.

1.2.4 Investigations of differences in analysis software packages

Due to the complexity of existing VLBI analysis software packages each IVS Analysis and Associate Analysis Center usually concentrates on the optimal use and development of just one software package. So far, within the IVS the three packages CALC/Solve, OCCAM, and SteelBreeze are being used for regular generation and submission of the various parameters. Anyway, a rigorous control of the results and an understanding of the differences will only be possible if many different software packages are used by the operational Analysis Centers. Therefore, routine processing with additional software is an important goal for the next few years.

Intercomparisons between software packages have been rather sparse in recent years. In order to understand differences and improve the overall quality of the results it is of great importance that inter-comparisons at regular intervals become a general task of the Analysis Centers.

1.2.5 Phase solutions for all baseline lengths

Investigations have shown that fringe phase delay observables can be used under very special conditions. So far phase delay solutions were only successful if stations are employed which provide very stable hardware in terms of inherent phase variations. As soon as more stations update their hardware with phase stable components phase delay solutions will become more practical and may be realized on a routine basis. With better modeling of ionospheric and atmospheric refraction effects baseline length will not be one of the limiting factors any more. More analysis of phase delays is required to determine possible systematic instrumental errors and to understand how important are intrascan phase variations.

1.3 Automation of the VLBI data analysis procedure - impacts, requirements, and concept

The time delay between the observation and the availability of results is a critical disadvantage of geodetic VLBI compared to other space geodetic techniques. One reason is the complicated and highly interactive analysis procedure, requiring well-founded expertise. While advances in e-VLBI technology promise to considerably shorten the delay, automatic VLBI analysis tools still have to be developed to obtain VLBI results in near real-time. The following discussion covers the analysis of single VLBI experiments.

1.3.1 Impacts of the automation

The automation of the whole VLBI data analysis procedure allows to close the gap between the time of observation and the availability of results, i.e. a quicker turn-around can be achieved. The costs of operations per session will decrease, because the analysts will be relieved from their routine burdens. Thus, they can spent more time to improve the modeling or to investigate instrumental errors or what might be even more important the number of observing sessions can be increased without requiring additional manpower for data analysis. The management of the data analysis will be much easier, because it is based on an explicitly modeled standard procedure that is performed by automatic programs. Last but not least, the results of the data analysis are internally much more consistent, because the same analysis strategy is going to be used and all steps of the analysis procedure are performed similarily.

1.3.2 Requirements for the automation

Two consecutive steps are necessary to automate the analysis procedure:

1. Build a so-called *Structured Model of the VLBI Data Analysis Procedure*: This model represents the knowledge necessary for the data analysis, and should be based on the experience of several analysts. It is important for a successful automation to model all the required knowledge in a structured and formal way. Therefore, the processing strategy of the data analysis has to be characterized by several steps to be performed one by one. Following details should be given for each step:

   a. *Tasks*: the tasks of the current step of the analysis procedure.
   b. *Parameterization*: every task demands a special parameterization that depends on the results of previous steps of the analysis.
   c. *Models*: all models used during data analysis.
   d. *Approach*: the approach to perform the tasks.
   e. *Evaluation criteria (quality control)*: to evaluate the results of the current step of the data analysis.
   f. *Error sources*: to list all possible faults that can cause unsatisfactory results.
   g. *Trouble-shooting*: methods to correct for faults; they are assigned to an error source.

2. Implementation: the structured model of the VLBI data analysis procedure has to be implemented within the existing software packages. For this purpose the following components have to be developed:

a. *Control system*: to control the analysis procedure.
b. *Diagnosis system*: to examine unsatisfactory results.
c. *Therapy system*: to apply appropriate methods to handle errors or problems.

New modules have to be developed to realize these components within the existing software packages; existing interactive modules have to be automated. It should be noted that the *Structured Model of the VLBI Data Analysis Procedure* is just a recommendation for the automation of the data analysis. IVS Analysis Centers may apply these recommendations for the generation of their routine products but are still free to follow their own strategies.

The main scientific problem is step 1, because it is difficult to collect and formalize all the knowledge needed for VLBI data analysis. Moreover, analysts may proceed differently and may use different evaluation criteria. In this context it is highly desirable to establish a *Standardization Group on VLBI Data Analysis* in order to develop the *Structured Model of the VLBI Data Analysis Procedure.*

The main technical problem is step 2. First of all it is time consuming to modify the existing software packages so that they allow an automatic data analysis procedure with a success rate of almost 100%. Besides, it is a challenge to develop the control, diagnosis and therapy system because it is extremely difficult to represent all the necessary knowledge by algorithms. Thus, all groups working with a specific analysis software package should form a *Software Automation Group*.
Finally, it should be mentioned that technically more robust VLBI data and more uniform session set-ups and schedules will make any automation much easier.

1.3.3 Experiences from a research project on the automation of VLBI data analysis

First proposals for the automation of the VLBI data analysis were already made in the nineties (Schuh, 1993a,b) and later by Schuh and Schwegmann (2000). An automized VLBI analysis software was developed in Japan and succesfully applied in the Key Stone Project (Koyama et al., 1999).Within a research project on an "Embedded Expert System for the Automation of the VLBI Data Analysis" (Schwegmann and Schuh, 1999; 2000; Schwegmann, 2004) a first prototype was developed for the whole VLBI data analysis procedure using the Mark 5 Data Analysis System (CALC/Solve) starting from the results of the correlator. During the project a prototype of an automated analysis system was developed which has given some general insights into the automation of the VLBI data analysis procedure:

- The analyst cannot be fully replaced by an automated software package.
- For the automation even the most trivial facts have to be considered.
- The *Structured Model of the VLBI Data Analysis Procedure* is the basis for the automation.
- A database containing information about the VLBI stations should be build.

2. Atmosphere, Ancillary Data and Models

2.1 Use of numerical weather models

2.1.1 New mapping functions

In recent years mapping functions such as the Isobaric Mapping Functions (IMF; Niell, 2001) and the Vienna Mapping Functions (VMF; Boehm and Schuh, 2003, 2004) have been developed to make use of information on the state of the atmosphere contained in numerical weather models (NWM) e.g., as ECMWF, NCEP, HIRLAM, and DAO. The potential of numerical weather models with high temporal and spatial resolution and prediction capacity for the determination of mapping functions has been shown (Niell, 2000; Boehm and Schuh, 2004; Stoyanov et al., 2004). Still missing, however, are thorough tests with different software packages and comparisons among the different numerical weather models used for these mapping functions. Furthermore, independent test evaluations by comparison with radiosondes and with water vapour radiometers should be extended. Because of the demonstrated value, progress in numerical weather modeling should be watched carefully, so that new and better models can be used immediately.

2.1.2 Gradient models

In addition to their application for the generation of a priori hydrostatic gradients as calculated within IMF, numerical weather models should be used to investigate the azimuthal and zenithal deviations from the standard gradient models (e.g., Davis et al., 1993; Chen and Herring, 1997). Special care has to be taken of the wet part because of its large variability. Water vapour radiometers may be able to provide validation of the deviations of the azimuthally symmetrical wet delays that are calculated from the numerical weather models. On the other hand, tests have been carried out in Japan to estimate the high order variability of the wet gradients using a fine mesh numerical weather model such as the non-hydrostatic model with 1.5 km resolution. The capability of the model for predicting realistic wet gradients has still to be validated.

2.1.3 Turbulence models

The potential of the application of turbulence models to describe the inhomogenous atmosphere instead of using conventional gradient models should be studied. First studies based on water vapour radiometry are successful and promising (Emardson and Jarlemark, 1999).

2.1.4 Ionospheric parameters

VLBI is able to provide absolute ionospheric parameters above globally distributed stations (Kondo, 1991). First results from VLBI agree well with values derived by several analysis centres within the International GPS Service (IGS) and with the results from satellite altimetry missions (Hobiger et al., 2003). It is possible to study the behaviour of the ionosphere on long- and short-term time scales. Therefore, VLBI can be used as a source for global ionospheric models and/or as an independent validation technique for the results from other space applications. Concerning long-term studies of the ionosphere, for several stations VLBI observations cover about 2 complete solar cycles, i.e. more than 22 years. A fact that makes this technique extraordinarily well-suited on detecting trends or periods on such a long timescale.

2.2 Long term perspectives beyond 2010

Probably, numerical weather models (NWM) will not be accurate enough by 2010 to do a VLBI solution without estimating tropospheric parameters, but on the other hand the number of atmospheric parameters that are estimated could be significantly reduced, e.g. if the NWM were accurate enough to describe the variations only an average value had to be estimated. This is valid for the zenith delay as well as for any parameters describing the anisotropy.

Another question that will be of interest in the next years is the minimum elevation. In future, if much higher intrinsic delay precision is achieved by either making use of phase delay ambiguity resolution or of much wider spanned bandwidths, it may not be necessary to go to the very low elevation angles. So far, this is the only way to minimize the formal height uncertainty. Increasing the minimum elevation would considerably reduce the demands on the atmospheric models. On the other hand there is more information about the atmosphere if low elevations are included. However, it seems likely that the lowest elevations will be used to which the atmosphere model does not degrade the solution, much as it is done now.

2.3 Use of other instruments

2.3.1 Microwave radiometry and GPS: independent techniques for atmospheric corrections

In VLBI analysis, the correlation between the station heights and the tropospheric zenith delays is relatively high. For this reason, observations at low elevations are needed to separate the station heights and the zenith delays if no external information about the troposphere is available. Therefore experiments shall either be optimized to use the VLBI data themselves to estimate the atmospheric effect or to use independent atmospheric data in the analysis. In practice this means that all results of reproducibility of estimated baseline lengths are based on experimental data optimized for not using the independent techniques - simply because the schedulers have wanted to be on the safe side, in case data from the independent technique would not be available. In spite of this optimization difficulty, most studies have given comparable reproducabilities whether or not data from microwave radiometry were used (Elgered et al., 1991; Kuhn et al. 1991; Elgered and Davis, 1993; Emardson et al., 1999). These studies indicate that the optimum elevation cut off angle shall be around 20 degrees. This is in agreement with the general features presented by Herring (1986). Furthermore, it is worth noting that using radiometer data to correct VLBI observations at low elevation angles means extrapolation of radiometer observations at typically 18-20 degrees. This is in itself a rather uncertain technique.

The problem of extrapolation external independent atmospheric data can be partly avoided if GPS observations are used to estimate the total propagation delay. Using the European VLBI network and independent atmospheric estimates from GPS data implies improvements in the reproducibilities of baseline length estimates (Rioja et al., 2000).

Since almost all geodetic VLBI sites have collocated GPS receivers it seems interesting to carry out more studies using more data from many sites and for longer periods in order draw more general conclusions.

2.3.2 Clock synchronisation

It has been shown that VLBI can be used for precise synchronization of clocks distributed around the world. However, true time synchronization of clocks at two VLBI stations requires the measurement of instrumental delays within the receiver, cables and backend equipment. While this process was done manually to demonstrate the concept, operational time synchronization would need a precise, automated calibration system or strict configuration control with remeasurement after any change in the VLBI system.

The reverse of clock synchronization by VLBI is the use of external clock information to improve the strength of VLBI analysis. The clock offset between stations is strongly correlated with the site vertical parameters and the estimates of zenith troposphere delay. Consequently if accurate clock differences were available via satellite or land links, these parameters of geophysical interest would be estimated more reliably.

3. New goals to be aimed at by VLBI

New goals arise for scientists due to the increasing accuracy of VLBI data as well as progress in data analysis. The most essential research directions are discussed below.

3.1 ICRF

The question how many radio sources should be within the ICRF cannot easily be answered because there is a variety of users (geodesy, space navigation, astrometry, astronomy). But ~600 defining sources and in total ~ 4000 sources (i.e. one per 10 deg^2) seem to be quite desirable for the ICRF. For EOP monitoring a few dozens of stable sources have to be identified.

For the ICRF improvement it is important to fix a list of truly stable radiosources because using unstable radiosource as 'defining' ones can cause problems for all further investigations. For example, the source 2145+067 (Fig. 1) selected as 'defining' in the current ICRF realization (Ma et al., 1998) was later classified as 'highly unstable' (Feissel-Vernier, 2003). It is obvious that every stable source can become suddenly an unstable one due to physical processes in its central core. Therefore monitoring of stability of all defining source would be essential, too.

Instabilities of the radio source positions due to unpredicted image fluctuations dominate in the daily coordinate time series. Nevertheless, some regular effects can be studied beyond the problem of image instabilities. The apparent motion of the sources is supposed to be systematic globally; therefore, search of any systematic changes looks promising. The presence of the absolute galactic rotation effect has been predicted on the level of a few microarcsec already by Sovers and Jacobs (1997). With the existing accuracy the effect can be detected from global analysis of all available VLBI data. Let us note, that the detection of the effect would provide the first estimate of the acceleration for the solar system barycentre relative to the quasars. This parameter is of significant physical and astronomical importance.

Some radio sources show non-random fluctuations of their coordinates. For example, a significant signal with a period of about 4.8 years and an amplitude of more than 0.2 milliarcsec has been detected for the time series of right ascension of source 2145+067 between 1993 and 2003 (Fig.1). However, so far the source has been assumed as point-like and was considered as a 'defining' one in the current ICRF realization. The study of such effects will allow to reduce the formal error of the ICRF as well as to understand the nature of the apparent signals.

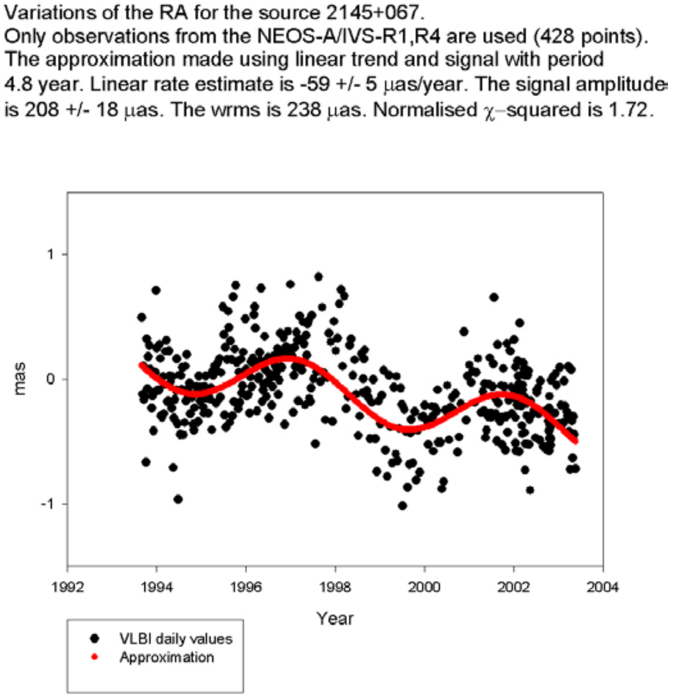
Including radio stars in geodetic/astrometric VLBI campaigns on a regular basis would make it possible to measure their proper motions and parallaxes as well as to link the ICRF and optical reference frames.

3.2 ITRF

Here, the most important contribution from VLBI is the provision of the scale. This is a strong argument why a global coverage of VLBI antennas is required with radio telescopes on all main tectonic plates.

The study of seasonal signals in both, VLBI baselines as well as site coordinate time series, appears to be important for the ITRF improvement during the next decade. The degree-one global seasonal deformation described by Blewitt et al. (2001) as ‘mode of the Earth’ can also be seen in VLBI data according to Lavaleé and Blewitt (2002). If its effect would be taken into account by very precise loading corrections this would reduce the power of seasonal signals of the observed geodetic time series.

Seismic events, like earthquakes can shift positions of fundamental VLBI sites by a few centimeters to meters. Therefore, another possible task is a more detailed analysis of pre-, co- and post-seismic motions of VLBI sites.



Variations of the RA for the source 2145+067.
Only observations from the NEOS-A/IVS-R1,R4 are used (428 points).
The approximation made using linear trend and signal with period
4.8 year. Linear rate estimate is -59 +/- 5 µas/year. The signal amplitude
is 208 +/- 18 µas. The wrms is 238 µas. Normalised χ-squared is 1.72.

Fig.1. Daily values of the right ascension time series for the source 2145+067 (1993-2003)

3.3 Linking of dynamical and quasi-inertial reference frames

Observations of artificial Earth satellites which emit on X- and S-band (or other radio frequencies) would make it possible to connect directly the dynamical reference frame and the ICRF. This would allow a combined solution of VLBI and dynamical methods such as GPS and SLR with an accuracy on the picosecond level.

3.3. 1 Pulsar timing

Observations of pulsars are considered as a method to improve the accuracy of the tie between the ICRF and a dynamical coordinate system defined by the DE/LE and other Solar system ephemerides. Pulsar signal time of arrival depends on the distance between the

Earth and the pulsar, and thus varies as the Earth moves around the Sun. Thus, measuring the arrival time of millisecond pulsar pulses (pulsar timing), along with measuring the pulsar positions w.r.t. extragalactic (ICRF) radio sources provides an important information for the tie of the dynamical coordinate system and the ICRF with milliarcsecond accuracy (Bartel et al., 1996).

3.3.2 Spacecraft observations

VLBI observations of a spacecraft traveling through the Solar system allow us to determine its orbit with high accuracy, which in turn depends on the orbit and gravitational fields of planets, their natural satellites and asteroids. Since the accuracy of VLBI observations is much higher than of optical ones, these observations help to improve Solar body ephemerides and extend our knowledge about the gravitational field, dynamical figures, and rotation of the Moon and planets. Examples are spacecrafts passing, orbiting around, or landing on Mars, and Venus orbiters observed by VLBI and used for improvements of Solar system ephemerides. Moreover, differential VLBI observations of such spacecrafts w.r.t. extragalactic radio sources is one of the main tools for orientation of the DE/LE and other Solar system ephemerides w.r.t the ICRF.

3.4 Earth orientation parameters (EOP)

Earth orientation parameters (EOP) are assumed to be affected by numerous effects on the time scale from a few minutes to several decades. For the high frequencies only diurnal and semi-diurnal time bands have been investigated up to now. Actually, the current status of VLBI programs does not allow to obtain permanent time series of EOP. Only special continuous campaigns (e.g., CONT94, CONT95, and CONT02) produced one-week or two-week-long time series convenient for analysis of EOP on sub-diurnal scales. A preliminary analysis shows a presence of sub-diurnal signals in the UT1-UTC time series after elimination of tidal terms.

For nutation there are two aspects to be considered: 1) For resolving the many short nutation periods in a foreseeable time a high sampling is required and 2) for monitoring the Free Core Nutation (FCN) regular observations are needed because the FCN is unpredictable at the present level of our knowledge of the Earth's dynamics. A further target is the Free Inner Core Nutation (FICN) predicted between 500 and 1300 days for which the search has to be continued. Figure 2 shows a spectrum of the differences between the observed nutation series and the IAU model which can be improved only by means of new highly accurate VLBI observations. More details about discrepancies between observations of the celestial pole offset and the model can be found in Malkin (2004).

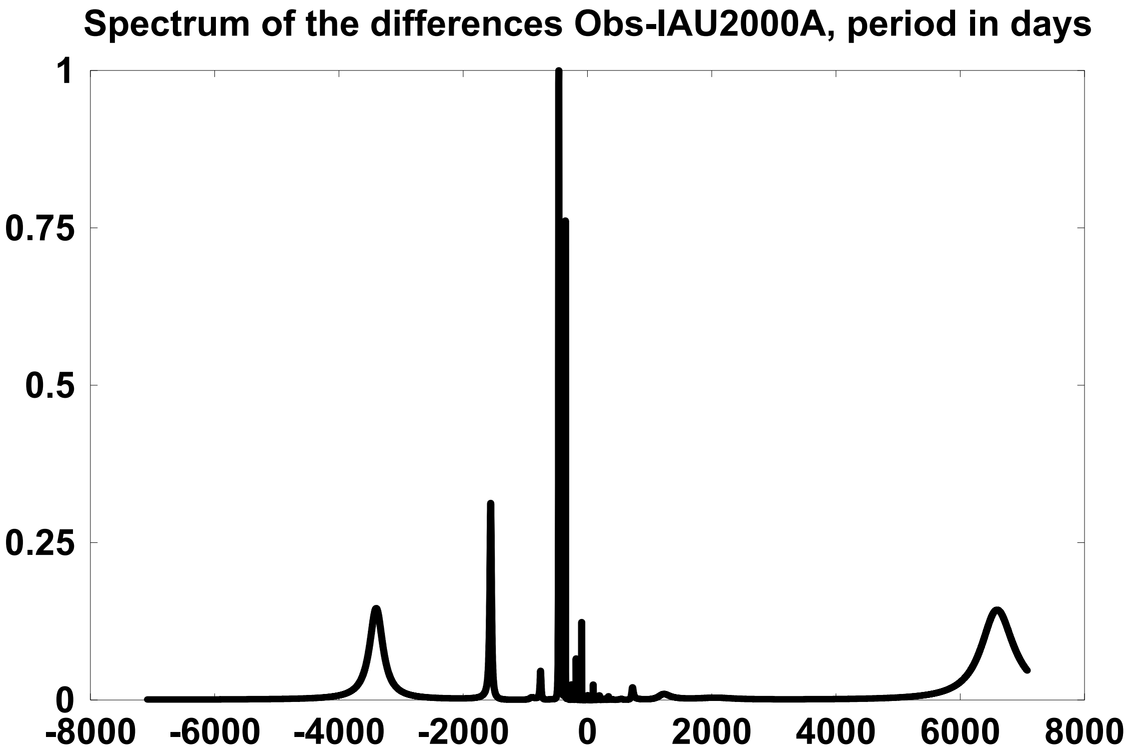


Figure 2. Spectrum of differences between the observed nutation series and the IAU model (period in days).

Another more theoretical aspect is the representation of Earth orientation by three Euler angles which can only be observed by VLBI.

3.5 Contribution to climatology

Since consistent VLBI observations have been carried out for more than 20 years, long time series of the wet zenith delays at various stations can be determined and used for climatological studies. Due to high instrumental stability VLBI appears has the potential to provide important complementary information to todays meteorological observation techniques (Boehm et al., 2003). The terrestrial reference frame has to be sufficiently accurate if we want to detect significant trends in the wet zenith delays, which is due to the relatively high correlation between station heights and zenith delays. Within the frame of the IVS Project ‘Tropospheric Parameters’, long time series of total and wet zenith delays will be compared and combined to get robust and reliable results for the long-term trends.The comparisons to independent techniques and combinations of results derived from different independent sensors are highly important (Haas et al., 2003c).

3.6 Contribution to relativity

In the next decade geodetic VLBI will remain an important source of information for the fundamental relativistic constants, and especially for the PPN parameter γ. Although future astrometric space missions like GAIA and SIM are expected to determine γ with an accuracy of 10^{-6}-10^{-7}, VLBI remains the only technique allowing one to observe close to the Sun as the minimal angular distance to the Sun amounts to a few degrees for VLBI and 30 to 50 degrees for dedicated astrometric space missions. This allows one to test also possible components of the gravitational time delay decreasing with the angular distance to the Sun faster than the main general relativistic effect. Thus, for the dedicated relativistic VLBI solutions it is desirable to use an extended model for the gravitational time delay including additional terms and parameters (other PPN parameters and post-linear parameters). Some other subtle gravitational effects like the additional gravitational time delays due to the translational motion of the gravitating bodies or due to their non-sphericity can also be measured by geodetic VLBI, but the relatively small number of observable sources makes it difficult to observe close enough to the giant planets (first of all, to Jupiter) where these effects have large amplitude. Space astrometry missions have better chances in this case. It is important to note, however, that VLBI measures the gravitational time delay and not the gravitational light deflection. Although these two effects are related to each other in the theories covered by the PPN formalism e.g., Einstein's general relativity, they may be independent of each other in some other theories. Therefore, from the point of view of fundamental physics it is important to improve the accuracy of VLBI solutions for γ and other relativistic parameters. Special care should be taken to ensure the stability and the repeatability of the dedicated relativistic VLBI solutions. Various possible sources of systematic errors should be thoroughly investigated. Clearly, the smaller the relativistic effect, this task becomes more and more complicated.

4. New VLBI configuration and observing systems

In recent years new ideas for VLBI configurations have been developed and new space missions have been proposed that make use of the VLBI principles by observations done by VLBI radiotelescopes using VLBI technology. Several of these missions are already going on or will be realized in the next future. This section gives examples of present Japanese projects.

4.1 Orbit determination of interplanetary spacecrafts using differential VLBI (DVLBI)

VLBI has its sensitivity in the plane perpendicular to the line of sight. This characteristic is complementary to range measurements, which have been traditionally used for navigation of spacecrafts in deep space. The joint use of both techniques is expected to enhance the precision of orbit determination. Differential VLBI (DVLBI) was used for spacecraft navigation sometimes by JPL. Now, researches on DVLBI application for spacecraft navigation e.g., by Ichikawa et al. 2003, Sekido et al. 2004, Walker 2004, Weimin 2004, are performed in several institutes to achieve more precise orbit determination.

More than 30 VLBI experiments for the two Japanese spacecrafts, NOZOMI ("Hope") and HAYABUSA ("Falcon") have been carried out from September 2002 until November 2003. In these experiments, the state-of-the-art K5 VLBI system was used for data acquisition and correlation processing. The K5 system is the multiple PC-based VLBI system equipped with a PCI-bus Versatile Scientific Sampling Processor (VSSP) board, which runs on the FreeBSD and Linux operating system. The K5 system includes the original software packages which are for data sampling and acquisition, real-time TCP/IP data transmission, and correlation processing. For the purpose of analyzing the DVLBI observables the specific VLBI delay model for finite distance radio source was developed. A new correlation software package to extract phase delay is also under development to determine the spacecraft position more precisely (Sekido et al., 2004). At present, delay and delay rate observables obtained from the VLBI experiments are available with a time delay of approximately 30 hours. This delay will be decreased as the capability of the high-speed network will be expanded to the entire globe. In addition, since the processing speed and efficiency is improving using multiprocessor and high-speed networks, the process time for the VLBI data correlation will be decreased, too. Technology development is going on for real-time and quasi real-time positioning of the spacecrafts using DVLBI in near future.

4.2 Observation of the lunar ephemerides and gravity field using Doppler and differential VLBI

In the SELENE project, which is the Japanese lunar exploration mission with launch in 2005, it is planned to apply the multi-frequency VLBI (Kono et al., 2003) to measure angular distances between two radio sources on board of two sub satellites orbiting around the Moon (Vstar and Rstar). The Japanese domestic network VERA and an international VLBI network will be used for the mission which is called ‘differential VLBI radio sources’ (VRAD) (Hanada et al., 2002). The radio transmitters emit three carrier waves in S-band and one wave in X-band and special recording systems as well as conventional ones such as K-4 receive the waves through VLBI antennas and determine phase differences between them within 10 degrees.

In cooperation with four-way Doppler measurements and two-way Doppler and ranging measurements by using the main orbiter and Rstar (Namiki et al., 1998; Iwata et al., 2001; Matumoto et al., 2002) VRAD will improve the accuracy of the spherical harmonics of the lunar gravitational field and the lunar ephemerides by one or two orders of magnitude. VERA will take part in VRAD for the whole mission period of one year and it is planned to conduct two intensive observation sessions each of them consisting of a one month period under participation of foreign stations.

5. Goals and tasks for the IVS

5.1 Action items before 2010

- loading modeled by best-practice
- establish local monitoring systems of antenna deformation and improve modeling
- full implementation of the IAU Resolutions 2000
- improved statistical models for data analysis
- phase solutions for all baseline lengths
- VLBI complete solutions with consistency of TRF, EOP, and CRF (=> IGGOS)
- intra-VLBI combinations of complete solutions on SINEX level
- detailed comparison of software packages
- develop a *Structured Model of the VLBI Data Analysis Procedure*
- nearly full automation of data analysis
- use of numerical weather models for mapping functions and gradients
- selection of stable sources for ICRF and EOP monitoring
- contribution to spacecraft tracking
- differential VLBI of natural and artificial Solar system objects w.r.t. ICRF
- detailed comparison of various loading, non-loading, atmospheric models
- estimation of ionospheric parameters e.g., TEC numbers
- extending the list of IVS products (UT1 using Intensives, ionosphere maps, combined TRF and CRF, FCN, …)
- detailed investigation of systematic errors in the IVS products, including comparison with other techniques
- define IVS Analysis Conventions covering all effects which are unique to VLBI
- Implementation of PIVEX data format

5.2 Visions after 2010

- regular monitoring of source structure and flux variations and providing structure corrections for geodetic VLBI
- linking optical frames to the ICRF
- linking dynamical frames to the ICRF (by both, spacecraft and pulsar observations)
- pulsar timing
- continuous monitoring of EOP with very high resolution
- independent clock synchronization
- improve coverage of southern hemisphere to support the IVRF

5.3 Feedback to other subgroups of the IVS Working Group 3

- network structure (in particular, at least 5 regularly observing stations should be established in the Southern hemisphere to provide high quality of EOP, TRF, and CRF)
- technically robust data are needed
- uniformity with respect to session set-up and scheduling is required
- scheduling and observing strategyshould be re-considered

References

Bartel, N., Chandler, J. F., Ratner, M. I., Shapiro, I. I., Pan, R., Cappallo, R. J., 1996, AJ, 112, 1690

Boehm, J., Schuh, H., Tesmer, V., and Schmitz-Hübsch, H.: Tropospheric Zenith Delays Determined by VLBI as a Contribution to Climatological Studies, In: Proceedings of the 16th Working Meeting on European VLBI for Geodesy and Astrometry, held at Leipzig, May 9-10, 2003, edited by W. Schwegmann and V. Thorandt, Bundesamt für Kartographie und Geodäsie, Frankfurt/Leipzig, 237 - 245, 2003.

Boehm, J., and H. Schuh (2004), Vienna Mapping Functions in VLBI analyses, Geophys. Res. Lett., 31, L01603, doi:10.1029/2003GL018984.

Blewitt, G., Lavallée, D., Clarke, P., and Nurutdinov, K.: A new global mode of earth deformation: seasonal cycle detected. *Science*, 294, 2342-2345, 2001.

Clark, T.A., and Thomsen, P.: Deformations in VLBI antennas. NASA Technical Memorandum 100696, Goddard Space Flight Center, Greenbelt, Maryland, 1988.

Davis, J.L., G. Elgered, A.E. Niell, C.E. Kuehn, Ground-based measurement of gradients in the "wet" radio refractivity of air, Radio Science, Vol. 28, No. 6, pp. 1003-1018, 1993.

Emardson, T.R., and Jarlemark, P.O.J.: Atmospheric modelling in GPS analysis and its effect on the estimated geodetic parameters. *Journal of Geodesy*, 73(6), 322-331, 1999.

Feissel-Vernier, M., Selecting stable extragalactic compact radio sources from the permanent astrogeodetic VLBI program, A&A, 2003.

Fey, A. L., Chalot, P., VLBA Radio Reference Frame Sources. II. Astrometric Suitability Based on Observed Structure, ApJS, 111, 95-142, 1997.

Haas, R., Nothnagel, A., Schuh, H., and Titov, O.: Explanatory Supplement to the Section 'Antenna Deformation' of the IERS Conventions (1996). In: H. Schuh (ed.): DGFI Report Nr. 71, Deutsches Geodätisches Forschungsinstitut (DGFI), 26–29, 1998.

Haas, R., Nothnagel, A., Campbell, J., and Gueguen, E.: Recent crustal movements observed with the European VLBI network: geodetic analysis and results. Journal of Geodynamics, 35(4–5), 391–414, doi:10.1016/S0264-3707(03)00003-6, 2003a.

Haas, R., Johansson, K.-Å., Elgered, G., Bergstrand, S., Gradinarsky, L. P., Stoew, B., Bouma, H., and Lidberg, M.: The IVS Network Station Onsala Space Observatory. In: N. R. Vandenberg and K. D. Baver (Eds.): International VLBI Service for Geodesy and Astrometry 2002 Annual Report, NASA/TP-2003-211619, 136–139, 2003b.

Haas, R., Elgered, G., Gradinarsky, L., and Johansson, J.: Assessing long term trends in the atmospheric water vapor content by combining data from VLBI, GPS, radiosondes and microwave radiometry. In: W. Schwegmann and V. Thorandt (eds.): Proc. of the 16'th Working Meeting on European VLBI for Geodesy and Astrometry, Bundesamt für Kartographie und Geodäsie, 279–288, 2003c.

Hanada, H., Iwata, T., Kono, Y., Matsumoto, K., Tsuruta, S., Ishikawa, T., Asari, K., Ping, J., Heki, K. and Kawano, N., VRAD mission; precise ovservation of sub-satellites in SELENE with international VLBI Network, Proc. 2nd. IVS General Meeting, 72-76, 2002.

Hobiger, T., Boehm, J., Schuh, H.: The project "VLBIonos" - how VLBI contributes to ionospheric research, In: Proceedings of the 16th Working Meeting on European VLBI for Geodesy and Astrometry, held at Leipzig, May 09-10, 2003, edited by W. Schwegmann and V. Thorandt, Bundesamt für Kartographie und Geodäsie, Frankfurt/Leipzig, 2003.

Ichikawa et al., An evaluation of VLBI observations for the positioning of the NOZOMI Spacecraft and the future direction in research and development of the deep space tracking using VLBI, IVS CRL/TDC News, No.23, 31-33, 2003.

IERS Conventions 2003, IERS Technical Note, D.D. McCarthy and G. Petit (eds.), January 2003.

Iwata, T., Takahashi, M., Namiki, N., Hanada, H., Kawano, N., Heki, K., Matsumoto, K. and Takano, T., Mission instruments for lunar gravity measurements using SELENE subsatellites, J. Geod. Soc. Japan, 47, 558-563, 2001.

Kondo, T.: Application of VLBI data to measurements of ionospheric total electron content, Journal of the Communications Research Laboratory, Vol. 38, No. 3, 613-622, Tokyo, Japan, 1991

Kono, Y., Hanada, H., Jinsong, P., Koyama, Y., Fukuzaki, Y.and Kawano, N. Precise positioning of spacecraft by multi-frequency VLBI, Earth Planets Space, 55, 581-589, 2003.

Koyama, Y., Heki, K., Takahashi, Y., and Furuya, M.: “3.3.1 Data Analysis Software.” Journal of the Commmunications Research Laboratory, 46(1), 67-76, 1999.

Lavallée, D., and Blewitt, G.:Degree-1 Earth deformation from very long baseline interferometry measurements. Geophysical Research Letters, 29(20), 1967, 10.1029/2002GL015883, 2002.

Ma, C., Arias, E.F., Eubanks, T.M., Fey, A.L., Gontier, A.-M., Jacobs, C.S., Sovers, O.J., Archinal, B.A., Charlot, P., 1998,: The International Celestial Reference Frame as realized by Very Long Baseline Interferometry, A. J. 116, p. 516

Malkin, Z., Comparison of VLBI nutation series with the IAU2000A model, Proc. Journees 2003, St. Petersburg, Russia, Sep 22-25, 2003, in press.

Matsumoto, K., Heki, K. and Hanada, H., Global lunar gravity field recovery from SELENE, Proc. 2nd. IVS General Meeting, 381-385, 2002.

Milly, P.C.D., Shmakin, A. B., Global Modeling of Land Water and Energy Balances, J. of Hydrometeorolgy, 3, 284-289, 2002.

Munekane, H., M. Tobita, and K. Takashima: Groundwater-induced vertical movements observed in Tsukuba, Japan, Geophys. Res. Let. 2004 (submitted).

Namiki, N., Hanada, H., Tsubokawa, T., Kawano, N., Ooe, M., Heki, K., Iwata, T., Ogawa, M., Takano, T. and RSAT/VRAD mission groups, Selenodetic experiments of SELENE: Relay subsatellite, differential VLBI and laser altimeter, Adv. Space Res., 23, 1817-1820, 1998.

Niell, A.E.: Improved atmospheric mapping functions for VLBI and GPS, Earth Planets Space, 52, pp. 699-702, 2000.

Niell, A.E.: Preliminary evaluation of atmospheric mapping functions based on numerical weather models. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, 26(6-8), 475-480, 2001.

Nothnagel, A., Pilhatsch, M., and Haas, R.: Investigations of Thermal Height Changes of Geodetic VLBI Radio Telescopes. In: R. Lanotte and G. Bianco (eds.): Proc. of the 10th Working Meeting on European VLBI for Geodesy and Astrometry, Agenzia Spaziale Italiana, 121–133, 1995.

Petrov, L, J. -P. Boy, Study of the atmospheric pressure loading signal in VLBI observations, Journ. Geophys. Res., Vol. 109, 1-13, 2004.

Scherneck, H.-G., R. Haas, M. S. Bos, Station Motion Model, In: J. Campbell, R. Haas, and A. Nothnagel (eds.): Measurement of Vertical Crustal Motion in Europe by VLBI, published on behalf of the European Commission, ISBN 92-894-0763-8, 2002.

Schuh, H., Design of an Expert System for VLBI Data Analysis. in: Proceedings of the 8th Working Meeting on European VLBI for Geodesy and Astrometry, Dwingeloo, Juni 1991, Report MDTNO-R-9243, Survey Department of Rijkswaterstaat Delft, IV53-IV58, 1993a.

Schuh, H., An Expert System for the Selection of Parameters in SOLVE. in: Proceedings of the 9th Working Meeting on European VLBI for Geodesy and Astrometry, Bad Neuenahr, Sept./Oct. 1993, Mitteilungen aus den Geodät. Instituten der Rhein. Friedr.-Wilh.-Univ. Bonn, Nr. 81, ed. by J. Campbell and A. Nothnagel, 79-86, Bonn, 1993b.

Schuh, H., Estermann, G., Crétaux, J.F., Bergé-Nguyen, M., Van Dam, T., Investigation of Atmospheric and Hydrological Loading. IAG Symposium, Sept. 8-13, 2002, Wuhan, China, C. Hwang, C.K. Shum, J.C. Li (Eds.), IAG Symposia Vol. 126, Springer-Verlag, 123-132, 2004.

Schuh, H., Schwegmann, W. A vision towards automated real-time VLBI. Physics and Chemistry of the Earth, Vol. 25/12, 813-817, 2000.

Schwegmann, W., Schuh, H., On the Automation of the MarkIII Data Analysis System. Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Viechtach, 12.-13. Feb. 1999, ed. by W. Schlüter and H. Hase, 265-272, 1999.

Schwegmann, W., Schuh, H. Status of IADA: an Intelligent Assistent for Data Analysis in VLBI. International VLBI Service for Geodesy and Astrometry 2000 General Meeting Proceedings, ed. by N.R. Vandenberg and K.D. Baver, NASA/CP-2000-209893, 319-323, 2000.

Schwegmann, W., Ein eingebettetes Expertensystem zur Automatisierung der VLBI-Auswertung (An embedded system for the automation of VLBI data analysis). ph.d. thesis at the University of Bonn, 2004.

Sekido et al., VLBI Observation for Spacecraft Navigation (NOZOMI) Data Processing and Analysis Status Report, IVS 2004 General Meeting Proceedings, 2004.

Sovers, O.J. and C.S. Jacobs, Prospects for Determining Galactic Rotation from VLBI Measurements, Proc. of conference on Modern Problems and Methods of Astrometry and Geodynamics (Russian Academy of Sciences, St. Petersburg, Russia), 144-145 (September 1996), 1997.

Sovers, O. J, Charlot, P., Fey, A. L., Gordon, D., Structure Corrections in Modeling VLBI Delays for RDV Data, IVS 2002 General Meeting Proceedings, 2002.

Stoyanov, B., Haas, R., and Gradinarsky, L.: Calculating mapping functions from the HIRLAM numerical weather model. In: N. Vandenberg and K. Baver (eds.): IVS 2004 General Meeting Proceedings, NASA/CP-2004-212255, to be published, 2004.

Tesmer, V.: Refinement of the Stochastic VLBI Model: First Results. In: W. Schwegmann, V. Thorandt (eds): Proceedings of the 16th Working Meeting on European VLBI for Geodesy and Astrometry, Bundesamt für Kartographie und Geodäsie, Frankfurt/Leipzig, 207-218, 2003.

Tesmer, V., H. Kutterer: An advanced stoachstic model for VLBI observations and its application to VLBI data analysis. In: N. R. Vandenberg, K. D. Baver (eds): IVS 2004 General Meeting Proceedings, NASA/CP-2004-212255, to be published, 2004.

Titov, O., H. Schuh, Short periods in Earth rotation seen in VLBI data analysed by the least squares collocation method, IERS Technical Note 28, Paris Observatory, 33-41, 2000.

Tobita, M., H. Munekane, M. Kaidzu, S. Matsuzaka, Y,. Kuroishi, Y. Masaki, and M. Kato, Seasonal Variation of Groundwater Level and Ground Level Around Tsukuba, J. Geodetic Society Japan, 50, 2004 (in print).

Walker, C.R., Future Directions on the VLBA, IVS 2004 General Meeting Proceedings, 2004.

Weimin Zheng, Zhang Xiuzhong, Shu Fengchun, E-VLBI Progress of the Chinese VLBI Network, IVS 2004 General Meeting Proceedings, 2004.