TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

DIPLOMARBEIT

Importance of the Hartebeesthoek Radio Astronomy Observatory for the VLBI network

Ausgeführt am Institut für

Geodäsie und Geoinformation (E120-4)
der Technischen Universität Wien

unter Anleitung von
Prof. Dr. Johannes Böhm
Department für Geodäsie und Geoinformation (E120-4)
Höhere Geodäsie

und unter Mitwirkung von
Prof. Dr. Ludwig Combrinck
University of Pretoria, Hartebeesthoek Radio Astronomy Observatory

durch

David Mayer
Kiesgasse 2
1140 Wien

Wien, Februar 2015

Acknowledgements

First and foremost, I would like to thank my advisor Johannes Böhm. He has been supportive since the day I started and always, even in the busiest times, found a moment to help me with my concerns. His guidance helped me through the more difficult parts of research and writing my thesis. I could not imagine a better supervisor than him.

In the course of this thesis I had the chance to spend a year at the Hartebeesthoek Radio Astronomy Observatory in South Africa where I was able to see how VLBI is conducted on an observation level. I would like to thank all the people working there for welcoming me with open arms. In particular, I want to express my gratitude to Ludwig Combrinck for providing professional advice and having an open ear for my problems. I am also grateful to the Vienna University of Technology and the Hartebeesthoek Radio Astronomy Observatory for providing financial support and to the University of Pretoria for providing facilities and assistance.

Finally, I would like to thank my family and friends (too many to be listed here) for their constant support and friendship, they never failed to cheer me up in hard times.

Abstract

This master thesis provides an insight into the only fundamental geodetic station in Africa, the Hartebeesthoek Radio Astronomy Observatory (HartRAO). In particular, the Very Long Baseline Interferometry (VLBI), one of the space geodetic techniques present at the site, is examined in detail. It's importance for the whole network of stations is evaluated on the basis of typical VLBI results, such as the International Celestial Reference Frame (ICRF), the International Terrestrial Reference Frame (ITRF) and Earth Orientation Parameters (EOP). In order to provide a prediction of the importance of the station in the past, two datasets with real data were used, namely the continuous VLBI campaign from 2008 (CONT08) and IVS-R1 sessions from the year 2011 and 2012. HartRAO's possible contribution to the future VLBI2010 Global Observing System (VGOS) network is investigated as well which was done using simulated data for different telescope types (a 15 m legacy antenna, a VGOS antenna or two VGOS antennas) at HartRAO. A VGOS network similar to the ones suggested in the literature is used. Simulations and schedules are created with the Vienna VLBI Software (VieVS). The results from the real data sets suggest that HartRAO was and is one of the most important stations for the VLBI network. Especially EOP estimation is heavily dependent on HartRAO due to it's remote location. This effect is very prominent in the real data sets, with a formal error increase of about 50% for nutation and 50% to 100% for polar motion when HartRAO is removed from the network. It can be seen in the simulated VGOS network as well but, since the stations are more evenly distributed, it is not that prominent. Nevertheless, HartRAO is still the most remote station of the network and, therefore, contributes significantly to the estimation of EOP, with the error of polar motion becoming 40% larger when comparing the VGOS network without HartRAO with the VGOS network with a twin telescope at Hartebeesthoek (HartTWIN). Furthermore, HartRAO is of significant importance for the estimation of sources; in particular, sources on the Southern Hemisphere depend heavily on the African telescope.

Kurzfassung

In dieser Masterarbeit wird die einzige geodätische Fundamentalstation in Afrika, das Hartebeesthoek Radio Astronomy Observatory (HartRAO), näher betrachtet. Im Speziellen wird auf die Interferometrie auf langen Basislängen (VLBI), eines der weltraumgeodätischen Verfahren an der Station, eingegangen. Die Bedeutung dieser VLBI-Station für das gesamte VLBI-Netzwerk wird anhand typischer Produkte der VLBI, wie der himmelsfeste Referenzrahmen (ICRF), der erdfeste Referenzrahmen (ITRF) und Erdorientierungsparametern (EOP), evaluiert. Um nun die Beudeutung von HartRAO in der Vergangenheit abzuschätzen wurden verschiedene Datensätze berücksichtigt. Einerseits wurde die kontinuierliche VLBI-Kampagne im Jahr 2008 (CONT08), andererseits die IVS-R1 Experimente aus den Jahren 2011 und 2012 herangezogen. Der Beitrag von HartRAO zum zukünftigen VLBI-Netz (VGOS) wurde anhand künstlich erzeugter Daten geschätzt. Hierzu wurde simuliert welchen Einfluss verschiedene Teleskope (15 m Antenne, VGOS Antenne und zwei VGOS Antennen) an HartRAO auf die VLBI-Produkte haben. Ein VGOS-Netzwerk, welches gleichwertig zu den vorgeschlagenen Netzwerken in der Literatur ist, wurde zur Evaluierung verwendet. Die Simulationen und Beobachtungspläne wurden jeweils mit der Vienna VLBI Software (VieVS) erstellt. Resultate der realen Daten suggerieren, dass HartRAO eine der wichtigsten Stationen für das momentane VLBI-Netzwerk ist. Insbesondere das Schätzen der EOP ist stark von HartRAO abhängig, was an der Abgelegenheit (im Vergleich zu anderen VLBI-Stationen) der Station liegt. Ein Entfernen von HartRAO aus den Datensätzen resultiert in einem Anstieg des formalen Fehlers um 50 % für die Nutation und 50% - 100% für die Polbewegung. Eine gleichartige Systematik kann in den simulierten Daten gefunden werden, allerdings ist der Effekt bei Weitem nicht so prominent, da das Netzwerk aus mehreren besser verteilten Stationen besteht. Nichtsdestotrotz ist HartRAO nach wie vor die abgelegenste Station des Netzwerkes und somit von höchster Bedeutung für die Schätzung der EOP, mit einem Anstieg des formalen Fehlers der Polbewegung um 40%, wenn das VGOS-Netzwerk ohne HartRAO mit dem VGOS-Netzwerk mit zwei VGOS-Antennen an HartRAO verglichen wird. Des Weiteren ist HartRAO bedeutend für die Schätzung der Quellenkoordinaten. Insbesondere Quellen auf der südlichen Hemisphäre sind stark von Beobachtungen der Station HartRAO abhängig.

Contents

Chapter 1

Introduction

Very Long Baseline Interferometry (VLBI) is a space geodetic technique which observes extragalactic radio sources (quasars) at the edge of the universe in order to establish a reference frame on Earth and in space. Originally VLBI was developed by astronomers to determine accurate positions and spatial structures of radio sources in space. The technique achieves high angular resolution and, therefore, can be used to determine precise source positions and the orientation of the Earth in space. A VLBI network has roughly the same angular resolution as a telescope of the network size. Building on the early developments of VLBI for astronomers, the ability to compute very long baselines with high accuracy was then used by the geodetic VLBI community to determine a variety of Earth's parameters. A network of geodetic radio telescopes determines accurate baselines and can, therefore, measure the position, deformation and movement of the station on Earth. Most of the time extragalactic sources, called quasars, are observed but radio frequency emitting satellites have been used as well. The VLBI technique is the only space geodetic technique that is able to observe the full set of Earth Orientation Parameters (EOP). It is also the only technique that allows for the precise measurements of nutation and the Earth rotation angle (dUT1). It contributes to the International Terrestrial Reference Frame (ITRF) (Altamimi *et al.*, 2011), in particular the scale is defined by VLBI, and it is crucial for the maintenance of the International Celestial Reference Frame (ICRF) (Fey *et al.*, 2009). The International VLBI Service for Geodesy and Astrometry (IVS) (Behrend & Nothnagel, 2013), an international collaboration of organisations which operate and support VLBI components, has been working on the future of VLBI. A new generation network (VGOS) which should reach a new level of accuracy (1mm position and 0.1 mm/yr velocity), will be implemented in the next couple of years. New scheduling procedures, hardware and software are currently tested and installed to reach this passionate goal. Today a world wide network of organisations in many different countries (see Figure 1.1) is participating in VLBI observations. (Schuh & Böhm, 2013)

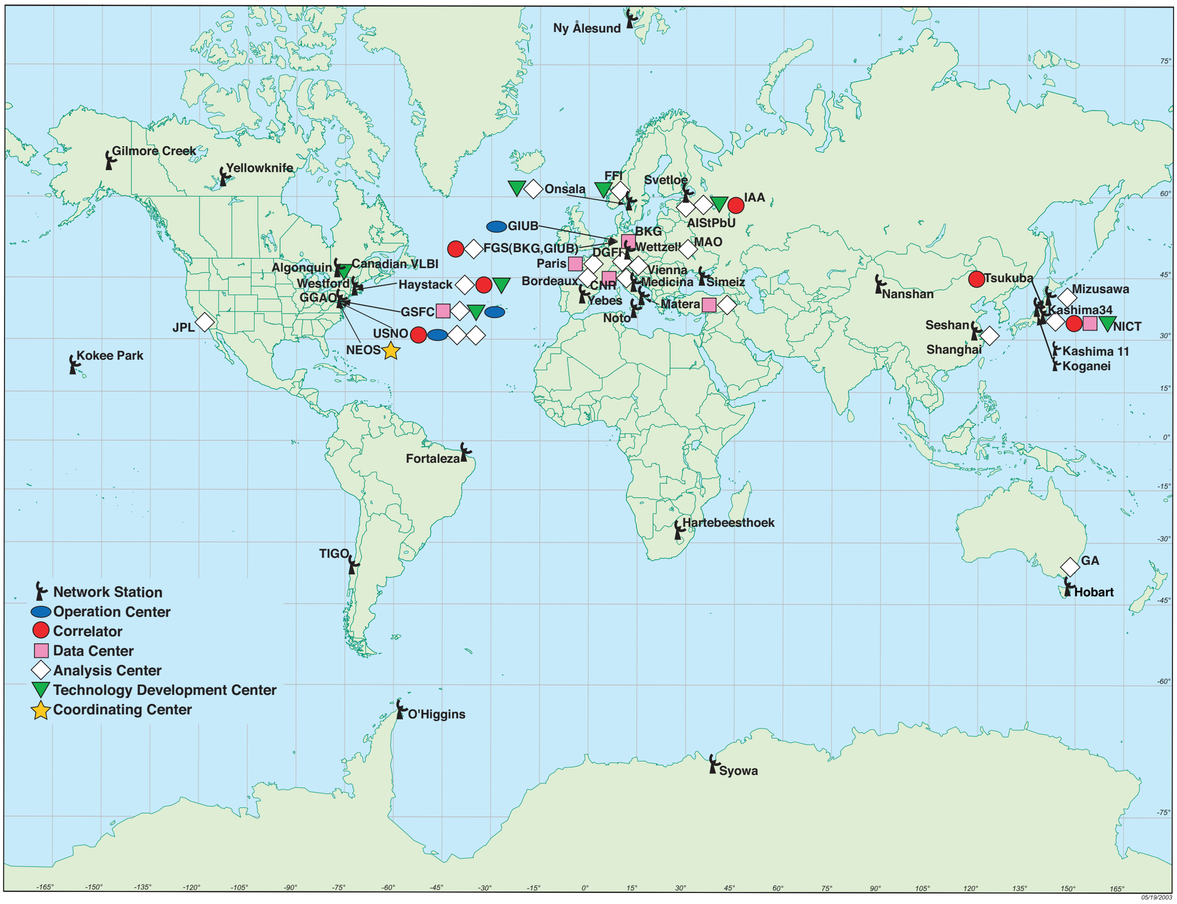

Figure 1.1: Distribution of different components (such as network stations, data centers, analysis centers etc.) of the IVS from http://ivs.nict.go.jp/mirror/about/org/components/ (2015/02/03).

1.1 Motivation

In recent years, the new VLBI2010 Global Observing System (VGOS - previously called VLBI2010) network is becoming a reality. All around the globe new VLBI sites are established and old hardware is upgraded. In particular, sites on the Southern Hemisphere are of interest. Petrachenko *et al.* (2009) expressed the problem of site distribution:

> "*An important aspect of VLBI2010 is the expansion of the IVS network toward a more uniform global distribution of stations. New VLBI2010 antennas are needed in all regions to improve connection to the ITRF and to improve the robustness of the ITRF scale. Therefore, a particular emphasis needs to be placed on the southern hemisphere where antennas are less plentiful. This is required to improve the CRF in the south celestial hemisphere and to reduce biases in source declination and station latitude due to global atmosphere gradients.*"

VLBI telescopes are very expensive in comparison to for example GPS antennas. Therefore, a new VLBI site has to be chosen with care and it makes sense to evaluate the impact of new station hardware on the network before it is built. This thesis provides a method and tools which help to evaluate the impact of an individual station on the current VLBI network. Furthermore, the same approach can be used for the assessment of new hardware in a network. This information is crucial for decision makers and can be used as an argument for funding.

Chapter 2

Theoretical background

2.1 Measurement principle

Quasars are radio galaxies at the edge of the observable universe; therefore, the emitted radio wave is assumed to be planar by the time it arrives at the observing stations. The VLBI observable is a travel time which is basically the difference between arrival times of the radio wave at two different stations. It is proportional to the offset of the two clocks and the projection of the baseline onto the source vector. In Figure 2.1 the measurement principle is illustrated, where (1) and (2) are the stations, $s(t)$ is the observed source and $\boldsymbol{b}$ the baseline vector. The time delay τ represents the elapsed time between recording time t_1 and t_2. (Schuh & Böhm, 2013)

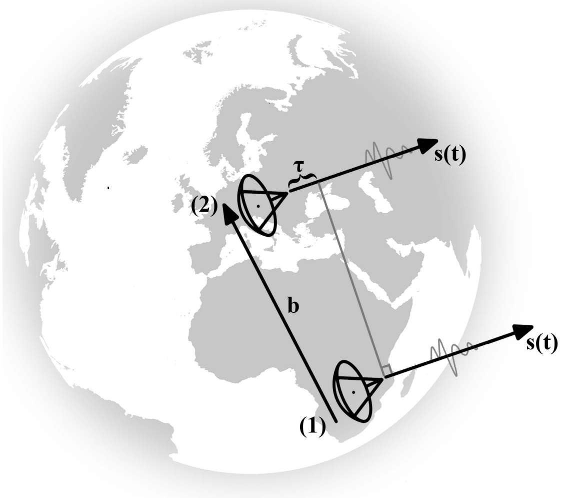

Figure 2.1: VLBI measurement principle. A wavefront is sent out by the source s(t) and arrives first at station (1) and after τ at station (2). The travel time τ is dependent on the projected distance between the two telescopes (baseline b).

The main observable of the VLBI technique, the time delay, can be calculated using the scalar product divided by the velocity of light c , see Equation (2.1).

$$\tau = (t_1 - t_2) = -\frac{\boldsymbol{b'} \cdot \boldsymbol{s}}{c}, \tag{2.1}$$

with

$$\boldsymbol{b'} = (b_x, b_y, b_z) \tag{2.2}$$

and

$$\boldsymbol{s(t)} = (\cos\delta\cos h(t), \cos\delta\sin h(t), \sin h(t)), \tag{2.3}$$

where b_x, b_y and b_z are the baseline components. The source position is described with δ (declination) and $h(t)$ (hour angle referred to Greenwich).

The baseline vector $\boldsymbol{b}$ is normally described in a terrestrial reference system, and the source position $\boldsymbol{s}$ in a celestial reference system. Hence, a transformation has to be done before Equation (2.1) can be calculated. The transformation from a terrestrial to a celestial reference system is realised with spatial rotations using five angles — the Earth Orientation Parameters (EOP). Two are used to describe the position of the Earth's rotation axis with respect to the celestial reference system (precession and nutation), one accounts for the differences in the Earth's rotation angle (dUT1) and two for the motion of Earth's rotation axis with respect to the terrestrial system (polar motion).

Equation (2.1) can be rewritten to

$$\tau = -\frac{1}{c}\boldsymbol{b'WSNPs}, \tag{2.4}$$

where

- $\boldsymbol{W}$ is the rotation matrix for polar motion,
- $\boldsymbol{S}$ is the diurnal spin matrix,
- $\boldsymbol{N}$ is the nutation matrix and
- $\boldsymbol{P}$ is the precession matrix.

Since the a priori EOP are not known with a sufficient accuracy (with the exception of precession) they are part of the estimation process and, therefore, are a result of the VLBI processing. (Schuh, 2000)

The recording principle is sketched in Figure 2.2. Two or more telescopes observe one quasar ($\boldsymbol{s(t)}$) at the time and each station saves the observed radio signal with a time stamp using a very precise atomic clock ("H-maser"). Quasars send out a broad band of radio frequencies and VLBI is currently observing 2 bands of this spectrum: the S-band (2.3 GHz) and the X-band (8.4 GHz). With observations in two bands the first order of the effect of the ionosphere which is a big error source for techniques using microwaves, can be corrected. After a session is finished the signal of each telescope is sent to a correlator where a cross correlation between signals is carried out. Background radiation and other disturbances distort the signal, this results in a extremely bad signal-to-noise ratio, but cross correlation is able to detect even small patterns hidden in this noise. The final outcome, the time delay $\tau(t)$ and the fringe rate $f(t)$, are then computed from the cross correlation function $R(\tau, t)$.

To obtain high resolution for the group delay a broad frequency band has to be observed. Unfortunately, digitising and saving a broad bandwidth produces a lot of data which is difficult to handle and expensive to store. This problem was solved by using the bandwidth synthesis technique. With this approach it is possible to get the accuracy of a broad bandwidth by observing smaller bands within and, therefore, getting a similar resolution with less data (Rogers, 1970). The observation of the phase delay which is common practice in the Global Navigation Satellite Systems (GNSS) technique, is not yet used in VLBI. This is due to the fact that a VLBI telescope can only observe one source at a time and has to be steered from source to source. During the slewing process the phase coherence gets lost because of several instrumental (mainly clock offset) and environmental factors (mainly atmospheric effects) (Campbell, 2000) and (Sasao & Fletcher, 2011). Petrov (1999) conducted successful experiments using the phase delay on very small baselines (1-10 km) where atmospheric effects can be neglected which provides very high accuracy. However, for longer baselines the matter is still an issue for further research.

In GNSS double differences are used to eliminate clock errors, unfortunately, this approach is not feasible in VLBI for the reasons mentioned above. Clock errors affect the observed delay directly; therefore, highly precise atomic clocks have to be used to keep the error as small as possible. Since VLBI observation times are quite long, the atomic clock has to be very stable. A clock that meets the needed requirements is the hydrogen maser (H-Maser) which is currently used by many VLBI stations.

For more details on VLBI, see Sovers *et al.* (1998) or Schuh & Böhm (2013).

2.2 Data acquisition

Two different construction designs are used for VLBI radio telescopes, namely the Cassegrain and the prime focus antenna. The signal arrives at a paraboloidal dish where it gets reflected to the feed horn (in case of the prime focus antenna) or to a hyperboloidal sub-reflector and then to the feed horn (in case of the Cassegrain antenna). A state of the art 20m VLBI telescope (see Figure 2.3) is situated at the fundamental station in Wettzell, Germany. Figure 2.3 depicts the signal path for the Cassegrain antenna (black lines).

A radio telescope has to meet certain requirements for conducting geodetic VLBI ex-

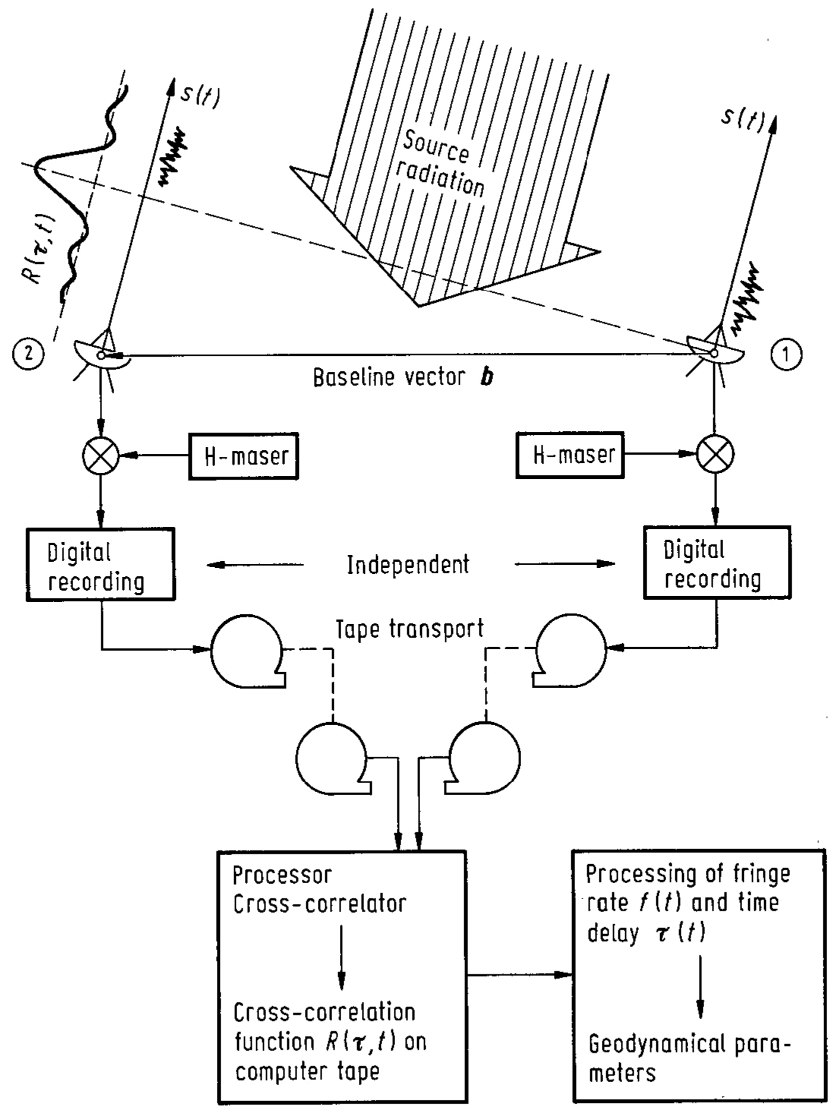

Figure 2.2: VLBI recording principle. (Mälzer, 1984)

periments. On the one hand the, dish has to be as big as possible to achieve an acceptable signal-to-noise ratio (the signal flux density is in order of 1 Jansky ($1Jy = 10^{-26}Wm^{-2}Hz^{-2}$) or even less) which keeps the time at a source at a minimum. On the other hand, it has to be as fast as possible to reduce the slewing time as much as possible. These requirements are contrary and, therefore, compromises have to be found. Today's antennas stretch from dishes with a diameter of 6m (Transportable Integrated Geodetic Observatory (TIGO)) to 300m (Arecibo Observatory). (Schuh & Böhm, 2013)

The feed horn is designed to receive S- and X-band radio waves. After being received the signal has to be amplified immediately to keep cable noise to a minimum. The amplifier has to be cooled down to 20 Kelvin ($-253°C$) in order to reduce inherent noise. To avoid high frequency effects, the signal is down converted to an intermediate frequency with a bandwidth

Figure 2.3: VLBI 20 m antenna from the fundamental station Wettzell[a] with signal path.

[a]http://www.wettzell.ifag.de/ (2013/03/05)

of, for example, 0 MHz - 350 MHz for the S-band and 80 MHz - 780 MHz for the X-band. After that the intermediate signal travels through a coaxial cable to the data registration system which is situated in a nearby building.[1]

The data registration unit first digitises the signal and then records it. For the digitisation the analog signal is first sampled and then clipped with usually 1- or 2-bit quantisation. In a 1-bit quantisation only the sign information remains but

> "*...we can completely derive functional form and, therefore, spectral shape of the original cross-correlation coefficient from an output* $R_{\hat{x}\hat{y}}[m]$ *of a digital correlator of the 1-bit quantized data, though the amplitude is reduced by a factor of* $\cong \frac{2}{\pi}$." (Sasao & Fletcher, 2011)

To record the data a very high data rate and a very large storage capacity are required. For a long time magnetic bands were the only devices able to meet the requirements but with the invention of the Mark 5 system (in 2002), where an array of hard drives is used instead, the tapes became obsolete. Mark 5 follow-ons (Mark 5A, 5B, 5A+, 5B+ and 5C) were released later on and a prototype of the new generation Mark 6 system was successfully used in October 2011.[2]

[1]http://www.fs.wettzell.de/ (2013/03/06)
[2]http://www.haystack.mit.edu/tech/vlbi/mark6/index.html (2013/03/06)

The usual approach is to send the tapes/hard drives via courier to a correlator where a cross correlation is conducted. This method entails long mail routes, hence, delayed results. The solution to the problem is called e-VLBI where data is directly transferred to the correlator over an optical fiber network. Some VLBI stations are already participating in e-VLBI but the connection of remote stations and the enormous amounts of data continue to be challenging.

2.3 Observation schedule

Before a VLBI experiment can be conducted an observation schedule has to be created. A variety of parameters, such as slewing time, source position and flux, dish diameter etc. influence a schedule. To acquire the optimal schedule for a session an optimisation criterion has to be chosen. In geodesy, uniform sky coverage is usually selected. With this approach the session is scheduled to cover as much of the sky as possible to achieve an efficient geometry. Uniformly distributed sources are also important to separate the tropospheric delay from the station height and clock error. (Schuh & Böhm, 2013)

A variety of scheduling software is available, e.g. the SKED scheduling package from the Goddard Space Flight Center (GSFC), Greenbelt (USA) or the VIE_SCHED module (see Chapter 2.4). Sun *et al.* (2014) compared the VIE_SCHED module with the state of the art scheduling package SKED and found a satisfactory agreement between generated schedules.

2.4 Analysis of VLBI data

The basic principle of every VLBI data analysis software package is depicted in Figure 2.4. It can be seen that the flow diagram contains two basic streams. In the left stream the actual observations are represented which are reduced by environmental factors (e.g. ionosphere, troposphere, source structure) and by instrumental factors (e.g. instrumental calibration, axis offset). The right stream contains the theoretical models, a priori station coordinates, EOP and source coordinates.

The two streams merge and create the observed-minus-computed vector (O-C). Parameters are then estimated by means of a least squares adjustment. With single sessions (usually 24 h) parameters such as station coordinates, EOP and the troposphere can be estimated. If more than one session is merged into a global solution, reference frames, geodynamical parameters and astronomical parameters can be estimated. (Schuh & Böhm, 2013)

There is a variety of VLBI data analysis software available which is of high importance, since more redundancy is reached and, therefore, errors can be located easier. In this chapter, however, the Vienna VLBI Software (VieVS) (Böhm *et al.*, 2012) is discussed since it is used in further analysis.

VieVS was written by the Institute of Geodesy and Geophysics (IGG), Vienna University of Technology. It includes state of the art models that coincide with the latest models for ocean tidal loading, atmospheric tidal loading etc., according to the Conventions of the International

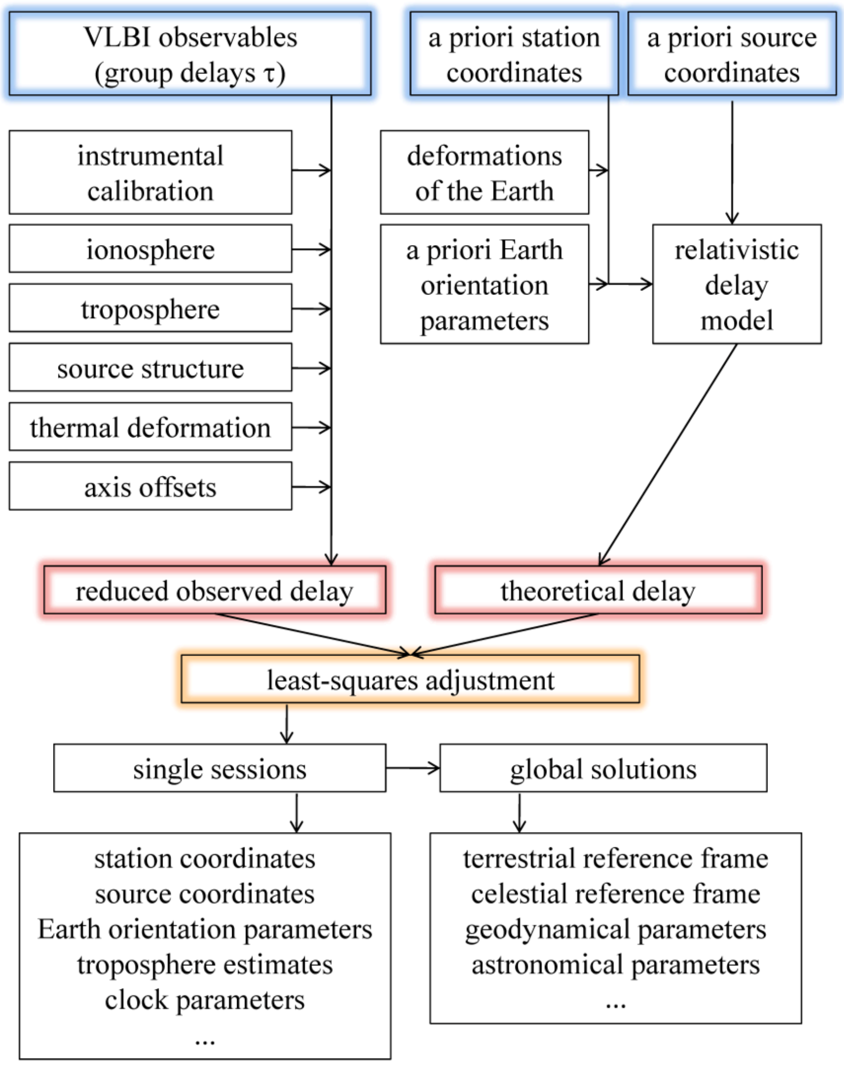

Figure 2.4: VLBI analysis model. (Schuh & Böhm, 2013)

Earth Rotation and Reference Systems Service (IERS) (Petit & Luzum, 2010). It is written in Matlab (version 7.6 (R2008a) or later is required) which provides the advantage of being easy to handle and the possibility of quickly applying source code changes. Unfortunately, Matlab is expensive and is not as fast as C++ or FORTRAN. Matlab is, however, widely used; hence, many research facilities are already in possession of a license. The slower speed is only a minor disadvantage, since today's computer hardware is fast enough for normal usage of the software.

VieVS is structured in different parts (a flow chart is illustrated in Figure 2.5). Main modules which are necessary for session wise VLBI analysis are depicted on the right:

- VIE_INIT (INIT stands for initialising), is responsible for reading the data; currently, VieVS needs session files (files with the actual measurements) in NGS format. Data created here is saved in the LEVEL 0 folder.

- VIE_MOD (MOD stands for modeling), calculates the theoretical delays, and its partial derivatives, state of the art models from the IERS conventions are implemented. Data created here is saved in the LEVEL 1 folder.

- VIE_LSM or VIE_LSM scan (LSM stands for least squares method), preforms the least squares estimation. Parameters such as EOP, station coordinates and clock offsets etc. are estimated and saved in the LEVEL 3 folder for further investigation.

Apart from the main structure in VieVS are three other modules, namely VIE_SCHED, VIE_SIM and VIE_GLOB:

- VIE_SCHED (SCHED stands for scheduling) is the scheduling package of VieVS. With this module an observation plan for a specific time and network can be created.

- VIE_SIM (SIM stands for simulating) creates simulated observations for an observation plan (could either be from a real session or scheduled). It combines the theoretical delay with simulated values for zenith wet delay, clocks and observation noise at each epoch, in order to create realistic observations. The output is saved as NGS format and can then be analysed with the main VieVS modules.

- VIE_GLOB (GLOB stands for global) combines the normal equations of several sessions into a global solution in order to calculate reference frames and global parameters.

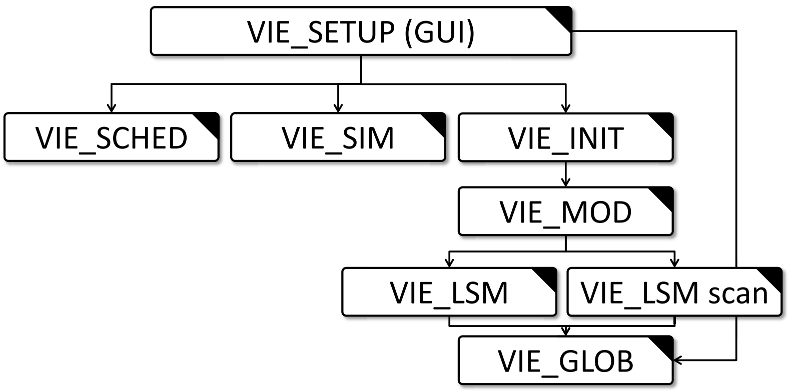

Figure 2.5: Different modules of VieVS.

Parameters and models can be easily selected using the graphical user interface (GUI) of VieVS (VIE_SETUP). The output is written to the command window of Matlab, the results are saved as Matlab files.

2.5 VGOS

Many VLBI telescopes used nowadays are decades old and equipped with outdated technology (developed in the 1960s). In 2005 the IVS decided to tackle that issue by investing in a new network of stations, equipment and software. (Schuh & Behrend, 2012) The new network is called VGOS an acronym which reflects VLBI within the framework of the Global Geodetic Observing System (GGOS). The aim of the next generation system was set to:

- 1 mm accuracy for position and 0.1 mm/yr for velocity on global scales
- continuous observations for time series of EOP
- results of sessions within 24 hours

To investigate the impact of new strategies Monte Carlo simulations have been carried out. It showed that one of the most important factors for higher accuracy is the source-switching interval and confirmed that the biggest error source is the atmosphere. If the source-switching interval decreases which includes shorter on source times and faster slew rates, the number of observed sources increases and, therefore, more redundancy and a better geometry is achieved. A recommendation for future VLBI antennas was given by the IVS research group, e.g. a single 12m diameter (or higher) telescope with very high slew rates, e.g. $12°/s$ or two 12m telescopes (or higher) with moderate slew rates, e.g. $5°/s$. Another technique to reduce the on source time is to increase the observed bandwidth. A system with four bands is recommended by the IVS which makes it possible to observe the entire frequency range from 2 to 14 GHz using the bandwidth synthesis technique. In order to save such huge amounts of data a registration unit with a data rate as high as 32 Gbps, or a transmission rate as high as 8 Gbps is needed. In order to reach highest accuracy, systematic errors, such as thermal deformation, electronic biases, mechanical stability, etc., have to be decreased as well. To do so exact calibration and deformation models are needed. (Petrachenko *et al.*, 2009)

In order to get a better geometry for the network, and hence more accurate EOP, an evenly distributed network with as many stations as possible is required. The IVS working group recommends that at least 16 VGOS stations observe every day to determine EOP and other antennas are added to maintain the CRF and TRF. A subnet of antennas should also be connected via a high speed optical fiber network to ensure solution in less than 24h. Since the southern hemisphere is rather poorly equipped the focus is placed on increasing the number of stations south of the Equator. (Petrachenko *et al.*, 2009)

2.6 Other space geodetic techniques

The SLR technique uses laser pulses to estimate the position and velocity of satellites. In order to do so the telescope shoots a very narrow laser pulse at a satellite that is equipped with a retro reflector. The travel time of the signal to the satellite and back is proportional to the distance between station and satellite. The basic principle can be seen in Equation 2.5:

$$d = \frac{\Delta t}{2} \cdot c, \tag{2.5}$$

where d is the distance between station and satellite, Δt is the measured travel time from station to satellite and back and c is the speed of light. Of course, in real life conditions many additional corrections, such as atmospheric, relativistic, etc. have to be applied.

The GNSS technique, in this case the Global Positioning System (GPS), uses a microwave signal modulated with a unique Gold Code per satellite. The antenna receives a mixture of signals from different satellites and cross-correlates it with locally generated Gold Codes. Using cross-correlation the travel time to each satellite in sight can be estimated. The basic principle can be seen in Equation 2.6

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc, \tag{2.6}$$

where $i = 1, 2, ..., n$ denotes the different satellites, p the pseudo range to each satellite, b the clock bias and c the speed of light. To solve for the receiver position at least four satellites have to be visible, since three coordinates and one receiver clock error have to be estimated. The simple equation needs to be corrected for a variety of environmental and technical influences, such as ionosphere, atmosphere etc.

For the sake of completeness the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system is mentioned here. It uses the Doppler effect to determine satellite orbits.

If two or more space geodetic techniques are at the same site we speak of co-location. Such sites are of high importance for combining the different techniques and estimating reference frames.

In Figure 3.2 the station HartRAO is depicted, co-located on this site is a GPS antenna, a SLR telescope and two VLBI antennas. The DORIS transmitter which is located behind a hill to prevent interferences with the VLBI telescopes is not depicted on this picture.

Chapter 3

The Hartebeesthoek Radio Astronomy Observatory (HartRAO)

In this Chapter a short history of the geodetic observatory HartRAO is provided, the VLBI equipment is discussed in detail and station coordinates and their movement are analysed.

3.1 History of the HartRAO station

HartRAO is one of the few fundamental stations on Earth which means that four space geodetic techniques (GNSS, SLR, VLBI and DORIS) are co-located at one site. Due to economical and political reasons most of the VLBI sites are located on the Northern Hemisphere. New telescopes, such as the AuScope network (Lovell *et al.*, 2013), have been built in Australia and New Zealand. However, Africa is still very poorly equipped with only one site — HartRAO — in a remote valley outside of the built up area (see Figure 3.1) in the Magaliesberg hills, 50km north-west of Johannesburg, in the province of Gauteng, South Africa (Latitude: $25°53'27.1''$ South, Longitude: $27°41'12.7''$ East) (Nicolson, 1995).

NASA built the Observatory in 1961 as a deep space tracking station. The 26m VLBI telescope, which is still in use, dates back to this time where it was used to send commands to, and get data from, US space probes. HartRAO was handed over to South Africa in 1975 and was converted to a radio astronomy observatory soon after. Since the 1980s the telescope is also used for space geodesy. In 2007 a 15m telescope was constructed as a prototype for the Square Kilometer Array (SKA)[1]. After completing its test phase the telescope was equipped with a new receiver with the goal to use it for geodetic VLBI, but radio astronomy research is also planned. A current picture of the station can be seen in Figure 3.2.

[1]http://www.ska.ac.za/ (2014/10/17)

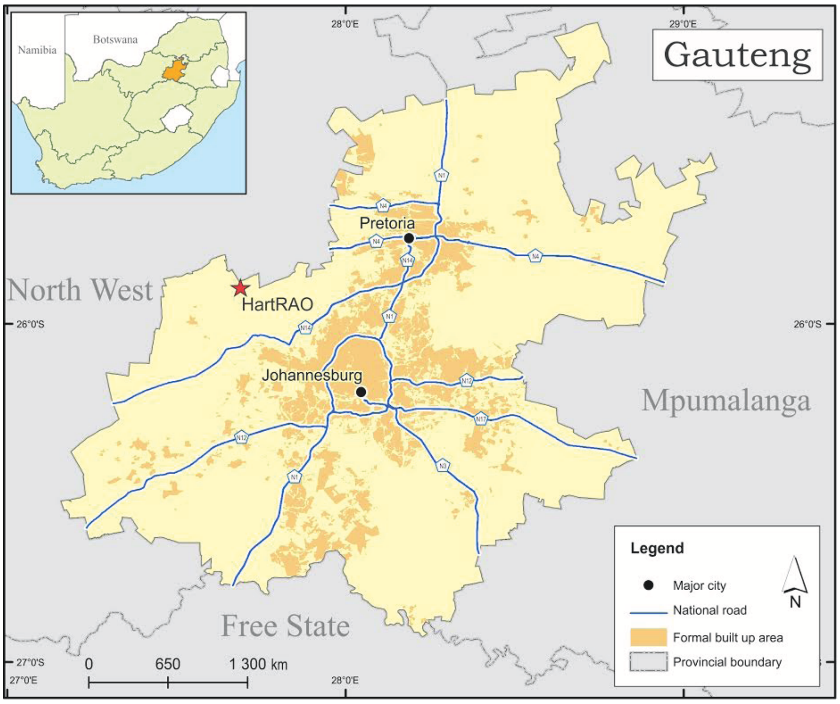

Figure 3.1: Map of HartRAO station.

3.2 VLBI equipment of the HartRAO station

Table 3.1 lists the technical details of the two telescopes. On the one hand the, 15m telescope has a faster slew rate then the 26m telescope which makes the source-switching time shorter. On the other hand, the System Equivalent Flux Density (SEFD), which is a measure of sensitivity of the telescope, is lower for the 15 m telescope which results in a longer on source time. The mounting of the telescopes also differs: while the 26m telescope is equatorial mounted, the 15m dish is placed on an azimuth-elevation mount. For comparative reasons a picture of both telescopes can be seen in Figure 3.3.

Table 3.1: Specifications of the 15m and 26m VLBI telescope at HartRAO

	26m telescope	15m telescope
Feed System	Cassegrain	Prime focus
Diameter [m]	25.9	15
Maximum slew rate on azimuth axis [deg/s)]	0.5	2
Maximum slew rate on elevation axis [deg/s)]	0.5	1
Pointing resolution [deg]	0.001	0.001
SEFD at S-band [Jy]	850	1050
SEFD at X-band [Jy]	1200	1400

The 15m telescope was equipped with a geodetic VLBI receiver in March 2012, since then the telescope participates in VLBI sessions on a regular basis. If the smaller telescope proves efficient, which it has done by now, it can relieve the 26m telescope of some of its geodetic

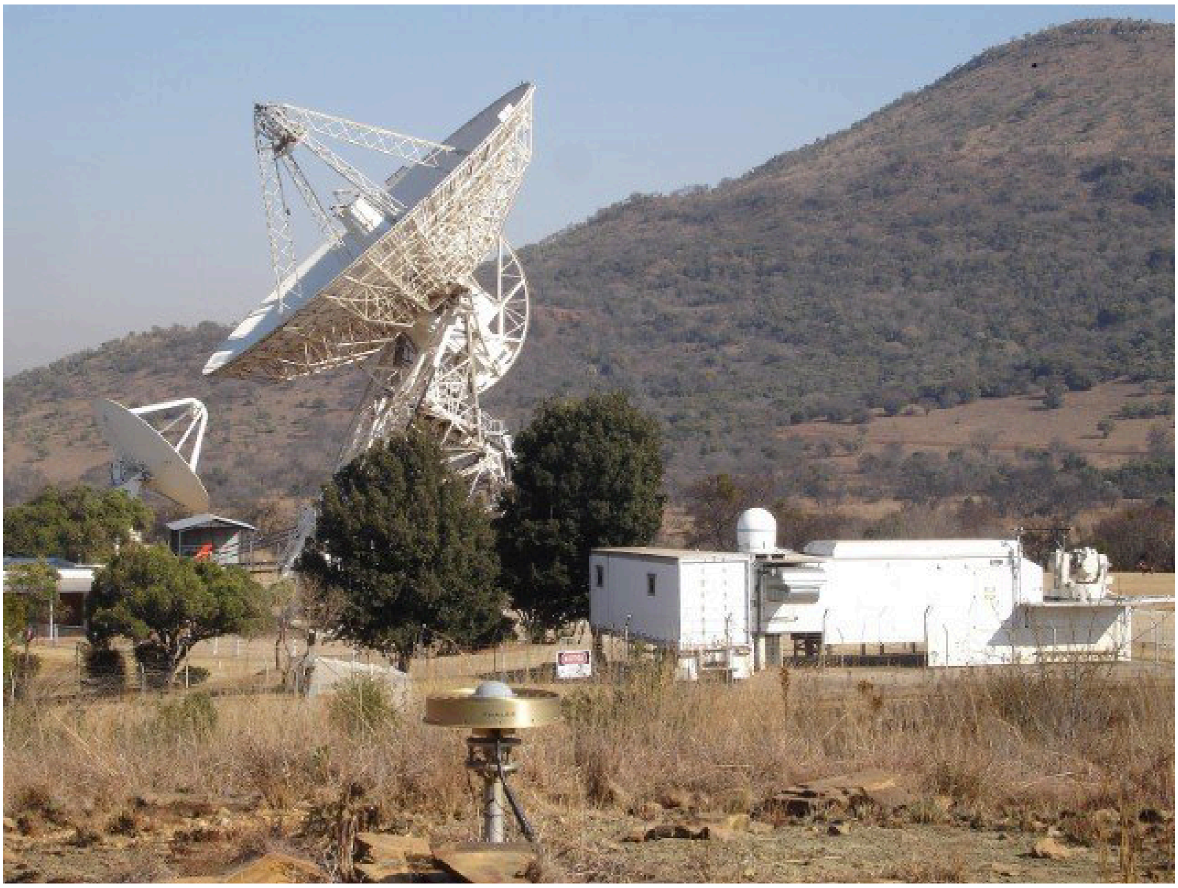

Figure 3.2: HartRAO station. Situated in the front is the GNSS antenna. On the right the Satellite Laser Ranger can be seen. Situated in the middle is the 26m telescope and left of it the 15m telescope.[a]

[a]http://www.hartrao.ac.za/summary/sumeng.html (2014/10/17)

VLBI duties, or both of them can be used in sibling mode, to increase observation density.

3.3 Station coordinates of the HartRAO station

In this section the coordinate time series of the HartRAO station is discussed. A simple analysis of VLBI data was conducted with the software VieVS. As a first step all sessions where HartRAO participated were selected and processed using the standard parametrisation. The primary function of the first processing step is to find corrupted sessions. A simple outlier test (to find erroneous observations) was applied and outlier files were created and used in further processing. The VLBI reference frame 2008 (VTRF2008) was used which is derived from VLBI observations before 2008. Station coordinates were estimated using the "No Net Rotation" and "No Net Translation" approach. Other estimation parameters and models were chosen according to the VieVS default settings which incorporates the newest IERS conventions. For more detail on the analysis strategy see Chapter 4.

Not all sessions are suitable for estimating station parameters, thus, certain exclusion

Figure 3.3: VLBI telescopes at HartRAO. On the left side the old 26m telescope can be seen. The newer 15m telescope is on the right.[a][b]

[a]http://www.hartrao.ac.za/hh26m_factsfile.html (2014/10/17)
[b]http://www.hartrao.ac.za/ht15m_factsfile.html (2014/10/17)

criteria have to be set. By examining the previously processed files the following exclusion criteria were found:

- the session must include 3 stations at least.
- the number of observations must be greater than 250.
- the a posteriori standard deviation of unit weight (chi-squared) must be smaller than 2.5.
- session without HartRAO.

These exclusion criteria are rather optimistic; therefore, a big coordinate scatter can be expected. Stations that are either corrupted or not suitable were excluded from the processing list. Final processing was conducted using all the suitable stations.

The variation of the telescopes xyz-coordinates over time is depicted in Figure 3.4. VLBI observations were conducted from 1986 onwards. Unfortunately, the time series was interrupted for almost two years since 2008. The disturbance is due to a failure of the bearing of the 26m telescope, it was, however, replaced in 2010. It can be seen that no data were recorded between 2008 and 2010. A linear trend was fitted to the data sets in order to estimate mean station velocities over time. While the x-coordinate is quite stable, the y- and z-coordinates drift off. The y-coordinate shows the biggest drift with approximately $2cm/year$. Estimated station velocities coincide with the VTRF2008 values (0.1 mm, 0.1 mm and 0.0 mm difference in the x,y and z coordinate respectively). The VTRF2008 uses all available data until 2008 to derive a priori coordinates. In this study data from the beginning of geodetic VLBI observations (1986) until July 2012 were used. The data used to estimate the station velocities overlap to a great extent (22 years) with the data used for estimating the VTRF2008 velocities. Therefore, the resulting velocities are very similar which is a good indicator that the results are trustworthy.

The movement of the xyz-coordinates are difficult to interpret on the site. To make the interpretation of the result easier the estimates and formal errors are transformed into a local East, North, Up (enu) coordinate system, using Equation 3.1:

$$\begin{pmatrix} n \\ e \\ u \end{pmatrix} = \mathbf{R} \cdot \begin{pmatrix} x - x_r \\ y - y_r \\ z - z_r \end{pmatrix}, \tag{3.1}$$

where x_r, y_r and z_r are coordinates of a reference point and $\mathbf{R}$ is the rotation matrix seen in Equation 3.2:

$$\mathbf{R} = \mathbf{M_x} \cdot \mathbf{R_y}(\frac{\pi}{2} - B) \cdot \mathbf{R_z}(L), \tag{3.2}$$

with mirroring around the x-axis ($\mathbf{M_x}$), rotation around the y-axis ($\mathbf{R_y}$, with the latitude B) and rotation around the z-axis ($\mathbf{R_z}$, with the longitude L).

Figure 3.5 depicts the transformed estimates. Since these values are relative to an a-priori value no reference point is needed. East and north components represent a tangent plane with origin at the telescope, and perpendicular to this plane is the up component. The up component is worse defined by a factor of approximately two. This is due to the fact that the horizontal station coordinates are estimated with observations over the whole horizon (360°), station heights are estimated with only observations from half a sphere (zenith distance +90° to 0°). Therefore, the up component is not as well defined as the north and east component.

This behavior can also be seen in the standard deviation in Table 3.2. It has to be noted that outliers were eliminated before calculating the standard deviation; however, outliers are still plotted in Figure 3.4 and 3.5. They were detected by estimating the standard deviation and using a 3σ band as threshold.

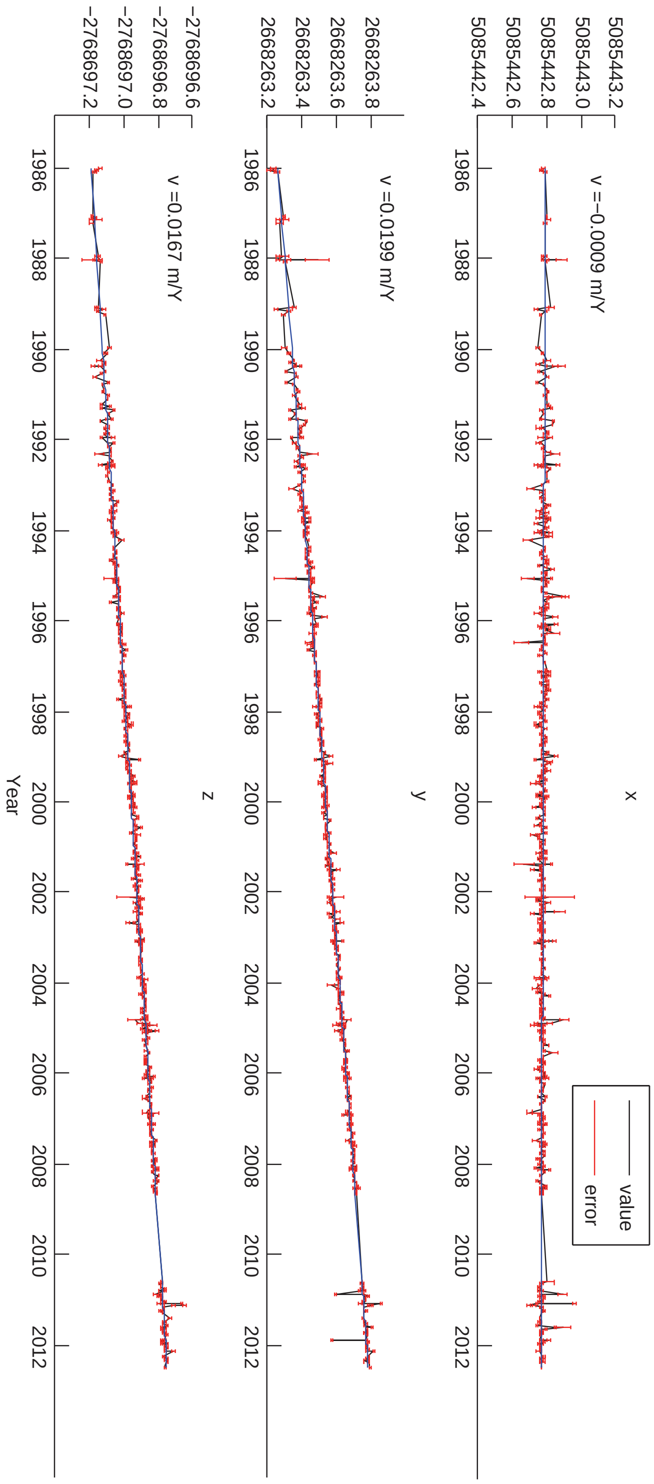

Figure 3.4: Variation of telescope coordinates over time.

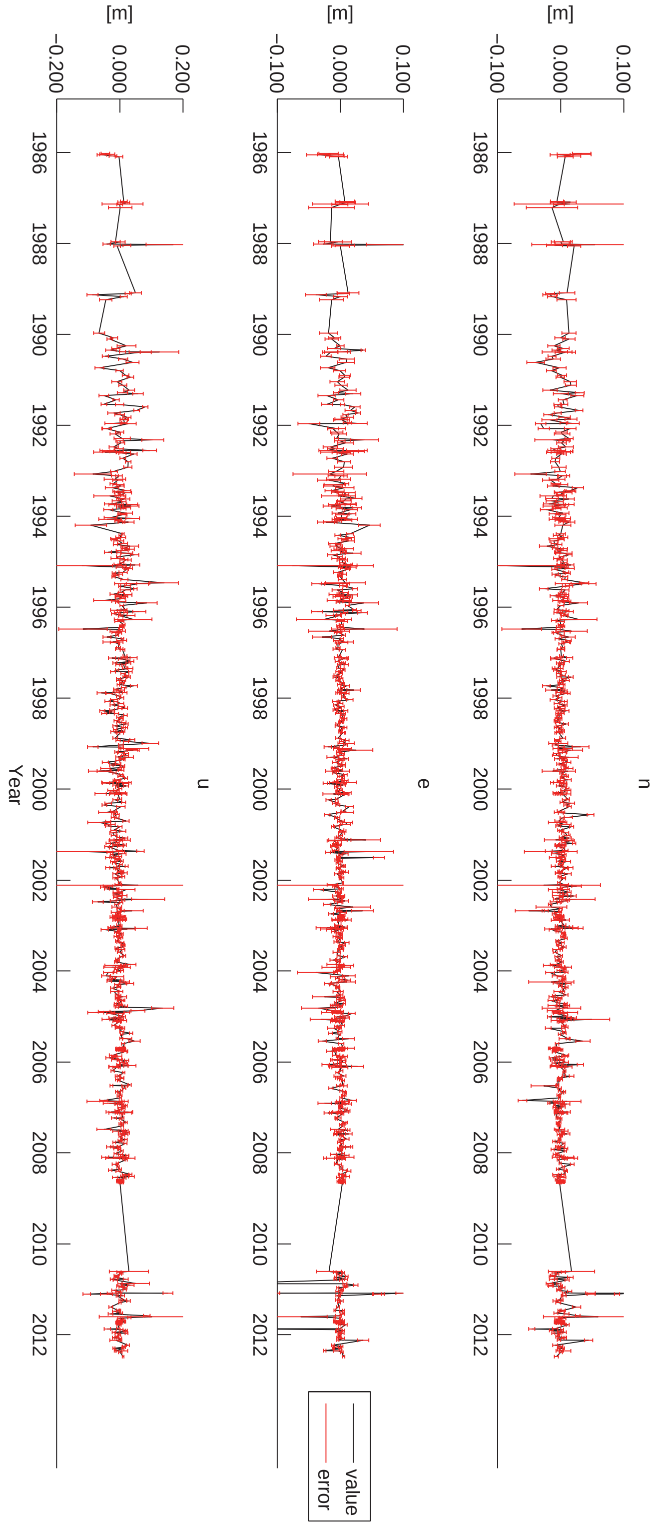

Figure 3.5: Variation of estimated parameters in a local horizontal coordinate system.

Table 3.2: Standard deviation and weighted RMS error of the estimated ENU coordinates

	Standard deviation [m]	Weighted RMS [m]
n	0.0091	0.0133
e	0.0084	0.0263
u	0.0208	0.0206

Chapter 4

Methodology

This chapter provides an overview of the used method and data and will answer the question “how do I evaluate the importance of a VLBI station”.

4.1 Used data

To evaluate the importance for the current VLBI network real data is used, see Section 4.1.1. Real data is not available for the future network; therefore, data has to be scheduled and simulated. A closer look into this procedure can be found in Section 4.1.2.

4.1.1 Real data

The analysis of real data was done on the basis of two data sets, namely the continuous VLBI experiment in 2008 (hereafter CONT08) and IVS-R1 data from beginning of 2011 until end of 2012 (hereafter IVS-R1). Real data is provided by the IVS. The measurements from all VLBI sessions (in NGS format) can be accessed online[1].

The CONT08 experiment

The CONT08 experiment was an uninterrupted 15 day campaign where 11 VLBI telescopes (the distribution of the network can be seen in Figure 4.1) participated. It took place from the 12th to the 26th of August 2008. The aim of these sessions was to calculate EOP with the highest possible precision. In order to achieve this goal the stations underwent extensive testing to assure that the hardware worked properly and to prevent failures during these sessions. (Behrend & Nothnagel, 2013)

[1] http://ivscc.gsfc.nasa.gov/products-data/data.html

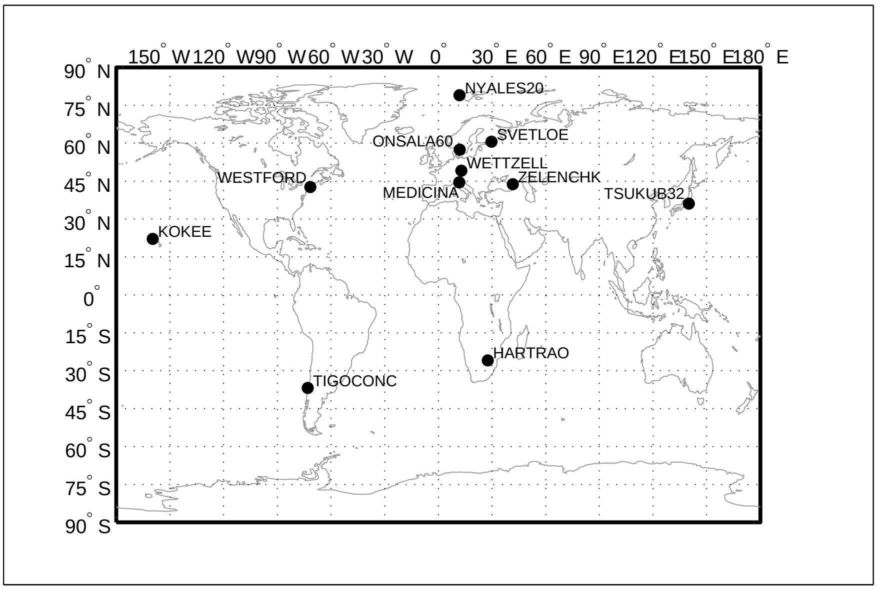

Figure 4.1: Station distribution of the CONT08 network.

The IVS-R1 sessions

The IVS-R1 and IVS-R4 sessions are scheduled twice a week (on Monday and Thursday respectively) with the purpose of regularly estimating EOP. For this analysis only IVS-R1 sessions are used since these are the sessions where HartRAO participates on a regular basis. The network usually consists of 9 - 10 stations which are globally distributed. A typical IVS-R1 network is depicted in Figure 4.2. Every station that participates is obliged to send the data to the correlator as soon as possible. This agreement should keep the turnaround time (the time from the measurement to the final result) to a minimum. (Behrend & Nothnagel, 2013)

HartRAO does not participate in all IVS-R1 sessions. Therefore, only sessions where HartRAO is included are used for this analysis. Sessions with errors that could not be fixed during the analysis are excluded as well.

4.1.2 Scheduling and simulation of data

In order to evaluate the importance of HartRAO for VGOS, a network with 18 stations (hereafter referred to as VGOS network) similar to one suggested by Sun *et al.* (2014) is used. A comparable network of at least 16 stations was also proposed by the IVS committee (Petrachenko *et al.*, 2009). In Figure 4.3 the station distribution of the used VGOS network is depicted.

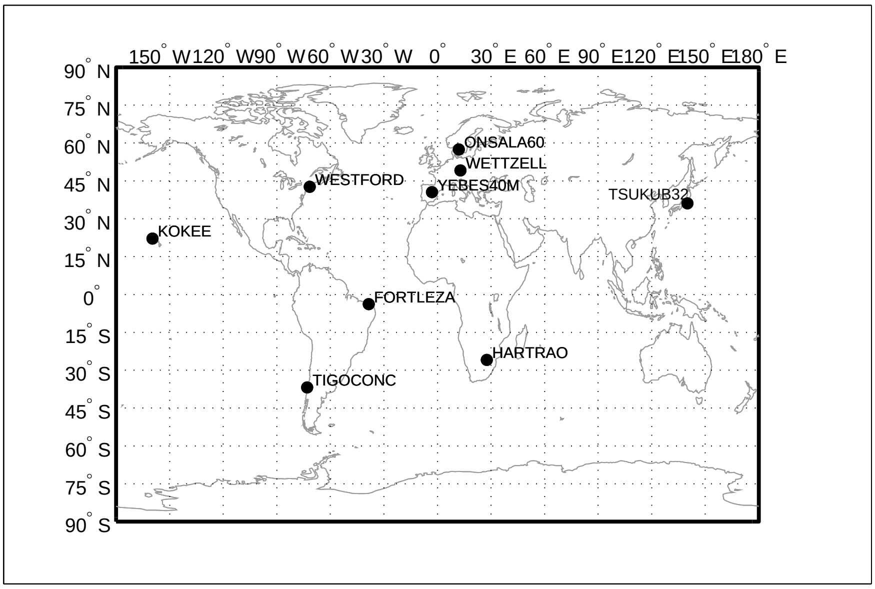

Figure 4.2: Typical station distribution of the IVS-R1 network.

The VGOS network

All stations in this network are equipped with fast slewing VGOS antennas with identical characteristics (no twin telescopes were used). Therefore, since all stations are identical and the troposphere is simulated, the influence of each VLBI site on the network is only dependent on the location of the station (geometry of the network) and the sources. Telescope parameters such as slew speed and diameter of the dish are neutralised.

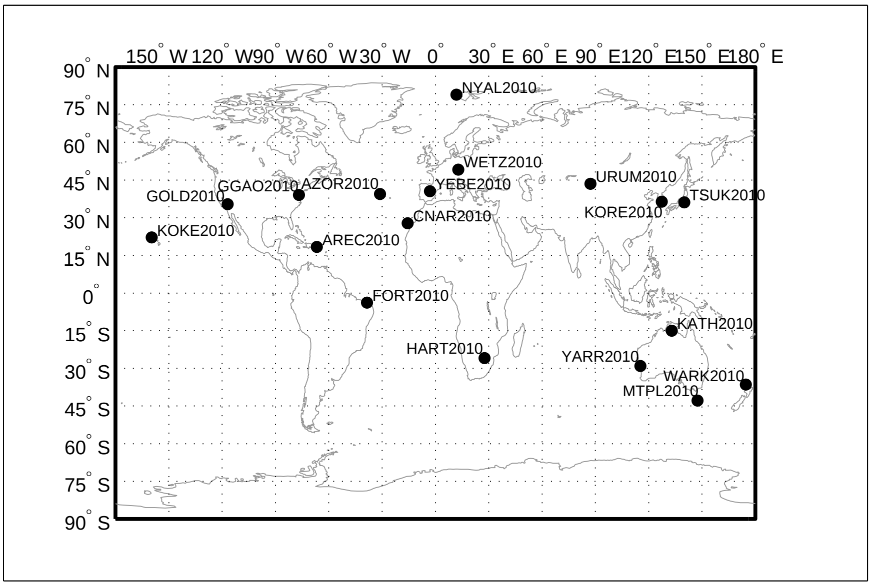

Figure 4.3: Station distribution of the VGOS network.

Scheduling of the VGOS network

As mentioned in Section 2.3 a VLBI experiment starts with a schedule. This is also true for the simulation of data, before observations can be simulated a schedule has to be present. Such a schedule can either be taken from an existing session (from the NGS file) or it can be drafted from scratch. Since the VGOS network is a fictional network a schedule is not available and, therefore, the first step in the analysis is to create a suitable schedule.

The schedule used in this analysis was drafted with the model VIE_SCHED which is included in VieVS. A station list, a date and some scheduling parameters have to be chosen in order to create a schedule. The date of the session was randomly set to the 21 of June 2012, the length was set to be 24 hours (standard length for a geodetic VLBI session).

Following scheduling parameters (this list only includes the major scheduling parameters) were set in VieVS:

- The minimal source flux density threshold was set to be $0.3Jy$.
- The sun distance is set to be more than 15°.
- A cut-off elevation angle of 5° was used.
- The observations were scheduled to be in S/X band, using 14 channels with a bandwidth of 128 MHz, a sample rate of 256 MHz and a quantisation of 2 bits was chosen. A minimum Signal-to-Noise Ratio (SNR) of 15 for S band and 20 for X band was selected.
- As scheduling strategy the "source based strategy" which maximises the source distribution in a global sense was used. For more information on scheduling see Sun *et al.* (2014).

A typical schedule drafted for the VGOS network with the parameters mentioned above has approximately 10000 scans and 100000 observations.

Simulating of artificial observations for the VGOS network

When a schedule is available artificial observations can be simulated. Basically, the theoretical delay is calculated and an additional delay due to simulated error sources, such as atmosphere, clock etc. is added for each scheduled observation (two telescopes observe one source). Therefore, the o-c vector, which is used in the least squares method, consists only of simulated delays, it can be calculated using Equation 4.1.

$$o - c = (wzd_2 \times mfw_2(el) + clock_2) - (wzd_1 \times mfw_1(el) + clock_1) + ss + wn, \qquad (4.1)$$

where $wzd_{1,2}$ and $clock_{1,2}$ are the simulated zenith wet delays (simulated with a turbulence model) and a delay due to clock errors (simulated as a sum of random walk and an integrated random walk) at the station 1 and 2 respectively and $mfw_{1,2}(el)$ are the corresponding wet mapping functions for the elevation angles el which are assumed to be without errors. Additionally, a factor for white noise (wn) is added per baseline. Recently, the source structure (ss) effect was included, it is added per baseline as well.

The simulation was done with the module VIE_SIM which is included in VieVS.

Following simulation parameters (Pany *et al.*, 2011) were set in VieVS (this list only includes the major simulation parameters):

- Troposphere parameters:
  - A refractive index structure constant C_n of $2.5 \cdot 10^{-7} m^{-\frac{1}{3}}$ was set.
  - The effective height of the wet troposphere was set to be $2000m$.
  - The wind velocity vector towards east was assumed to be $8\frac{m}{s}$.
- A power spectral density (Allan Standard Deviation; ASD) of 10^{-14}@$50min$ was used for the stochastic variation of the station clock.
- A factor of $16ps$ which resembles white noise (measurement error) was added to each computed baseline observation.
- Source structure was not simulated.

In principle, it is possible to choose simulation parameters for each station separately. However, since we only want to study effects due to the change of the station HartRAO, the parameters were exactly the same at each station.

In order to get statistics for each session and to account for random simulated errors each schedule was simulated 25 times (this number was empirically established — according to personal communication with Jing Sun).

4.2 Analysis of data

In order to analyse VLBI data an appropriate software package, such as VieVS (see Chapter 2), has to be chosen. For real data the network can be analysed once with and once without a station. The results can then be compared using different methods which are described in Section 4.3. With artificial data the chosen network can be simulated with different telescopes at one site and then be compared.

In the following analysis using the software VieVS, station coordinates, EOP, clock and atmospheric parameters were estimated. The default settings in VieVS were used, e.g. one constant parameter per 24 hours was estimated for EOP and station coordinates, the datum was set with the No-Net-Translation and a No-Net-Rotation (NNT/NNR) condition on all stations.

4.3 Means of comparison

Since VLBI delivers three major products (ICRF, ITRF and EOP) it makes sense to investigate the importance of the selected station on those products:

- Since the quality of source position (**ICRF**) is dependent on the number of observations to that source the impact of a station on the number of observations can be chosen as a measure of importance. Another possibility would be to estimate source positions and investigate the changes in formal error if the telescope is changed. Source positions, however, were not estimated in this analysis.
- The **ITRF** is dependent on the quality of station positions. A good measure for the quality of station coordinates is the baseline length repeatability. One can see from this plot how the whole network is affected when a station is removed or changed. The baseline length repeatability is the standard deviation or RMS (weighted or not weighted) of the baseline plotted as a function of the average length of the baseline. Another measure of station coordinate quality used in this investigation is the station vector repeatability. The length of the estimated station vector (estimates for the x-, y- and z-coordinate) is calculated, the standard deviation of the result is computed and then plotted for each station. Since the standard deviation is used in both measures a series of sessions (the whole data set) has to be used.
- In the analysis process **EOP** are always estimated. Therefore, one can use formal errors and estimates to investigate the importance of a station. This is done using statistics.

A measure which indicates the separability of these parameters is the **correlation**. It can also be used as a measure of comparison. The covariance matrix is used as input and the correlation is then calculated using Equation 4.2, 4.3 and 4.4.

$$Q = (A^T PA)^{-1}, \tag{4.2}$$

where Q is the covariance matrix, A is the design matrix and P the weight matrix.

$$\sigma = diag(Q), \tag{4.3}$$

with σ being the extracted diagonal (vector) of the matrix.

$$R = \frac{Q}{\sqrt{\sigma * \sigma'}}, \tag{4.4}$$

where R is the correlation matrix

Malkin (2009) suggested that the **network volume** is directly connected to the EOP quality. Therefore, a quick first overview of the importance of each station can be achieved by calculating the network volume and investigating the loss of volume when a station is dropped from the network. This, however, is only an approximation and provides only a rough estimation of the importance of a station for EOP estimation.

More details on the individual comparison strategies can be found in the continuing chapters respectively.

Chapter 5

Evaluating the importance of the HartRAO station for the current VLBI network

In this chapter the importance of the HartRAO station is evaluated using real data sets. It has to be noted that some of the results presented here have been published previously by the author, see Mayer *et al.* (2014).

5.1 Importance of HartRAO for the ICRF

VLBI is the only technique which is able to establish a celestial reference frame. In order to get evenly distributed sources in the ICRF we need stations at different latitudes. However, as seen in Figure 5.1 (upper plot), the distribution (in this case the ICRF2 is depicted) is not even with more sources on the Northern Hemisphere. This bias is due to the lack of southern stations. In this analysis the ICRF2 catalog was used as a reference, it has 697 sources north and 520 sources south of the Equator when only non VLBA Calibrator Survey (VCS) sources are considered (Fey *et al.*, 2009). For comparative reasons, Figure 5.1 depicts the distribution of the sources used in the CONT08 experiment as well (lower plot). In the CONT08 campaign the biased source distribution is even more pronounced with 80 sources used in total, 52 in the Northern Hemisphere and 28 in the Southern Hemisphere.

To quantify the contribution of HartRAO to the source observations during the CONT08 experiment, the network was once evaluated with and once without the station HartRAO. The number of observations for each source was calculated and summed up over all 15 sessions. The comparison is depicted in Figure 5.2. Here the sources are plotted as a function of their declination and the loss of observations per source is indicated in percent (with no contribution of HartRAO being 100 %). One can see that the further south a source is located (negative declination) the more it is dependent on HartRAO. The two most southern sources are even

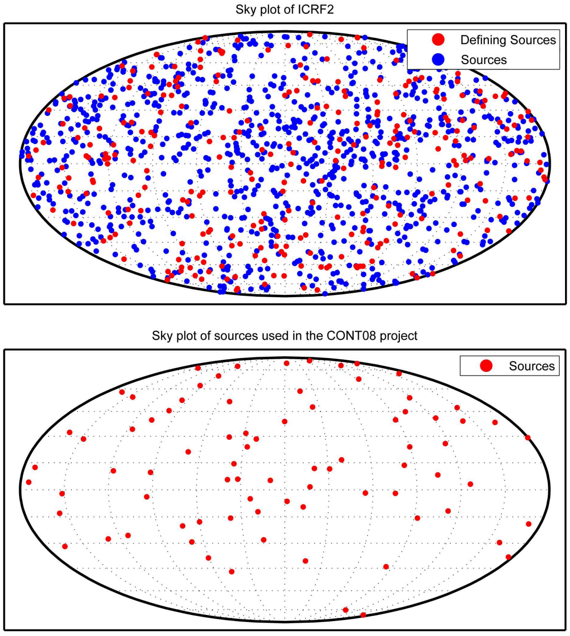

Figure 5.1: Upper plot: Source distribution of the ICRF2 (non-VCS sources). Defining sources have a high astrometric quality and are marked in red, sources marked as blue have either a high position variation or an insufficient observation duration. Lower plot: Observed sources of the CONT08 project.

omitted when HartRAO is excluded which means that those sources only have observations (in the CONT08 campaign) with HartRAO.

In Figure 5.3 a similar analysis is depicted with the difference that IVS-R1 sessions are used as data. It would not be fair to recreate the previous plot since the IVS-R1 sessions vary in station distribution. Therefore, the sources were divided in 10° intervals and observations to sources in segments are summed up. This was again done with and without HartRAO. One can see a similar behavior to the analysis where the CONT08 sessions were used. The further south a source is the more it is dependent on HartRAO. When HartRAO is dropped from the IVS-R1 network, observations to sources on the Southern Hemisphere, which are already low, decrease by 35% (average loss over 10° intervals).

The results from both investigated data sets suggest that HartRAO is of high importance, if sources on the Southern Hemisphere are observed which is due to it's remote southern location. It is, therefore, a crucial station for maintaining the ICRF. However, it has to be noted that real data was used in the analysis which results in a non-optimal schedule if HartRAO is dropped from the network. This makes the results too pessimistic since some of the loss could be compensated by rescheduling the network. A fair comparison would be to create two different schedules, one with and one without HartRAO, and observe both with similar conditions. However, such data were not available; therefore, the results presented here are more of a simulated case. A fair comparison can be found in Chapter 6, here different schedules where created when the telescope was changed. The down side is that the

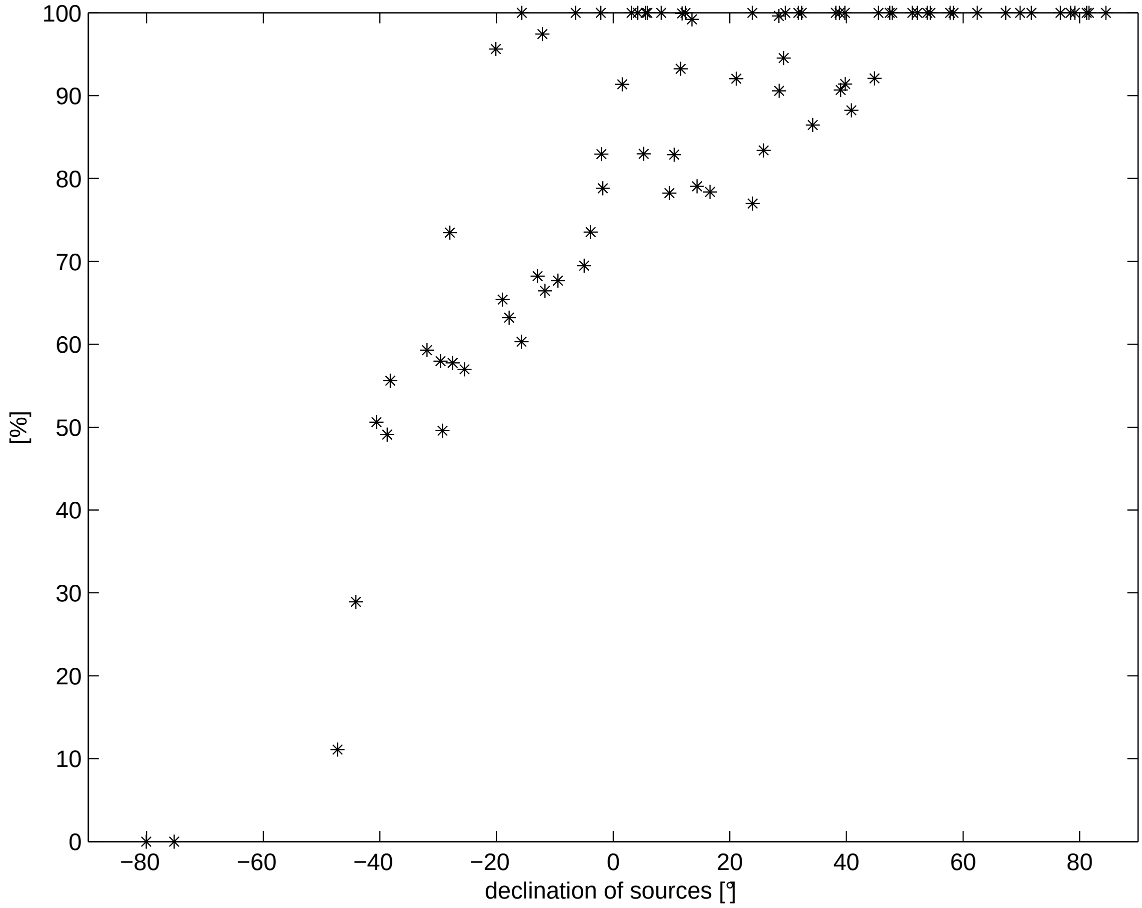

Figure 5.2: Sources of the CONT08 network - comparison of number of observations with and without HartRAO [%] and declination of the sources.

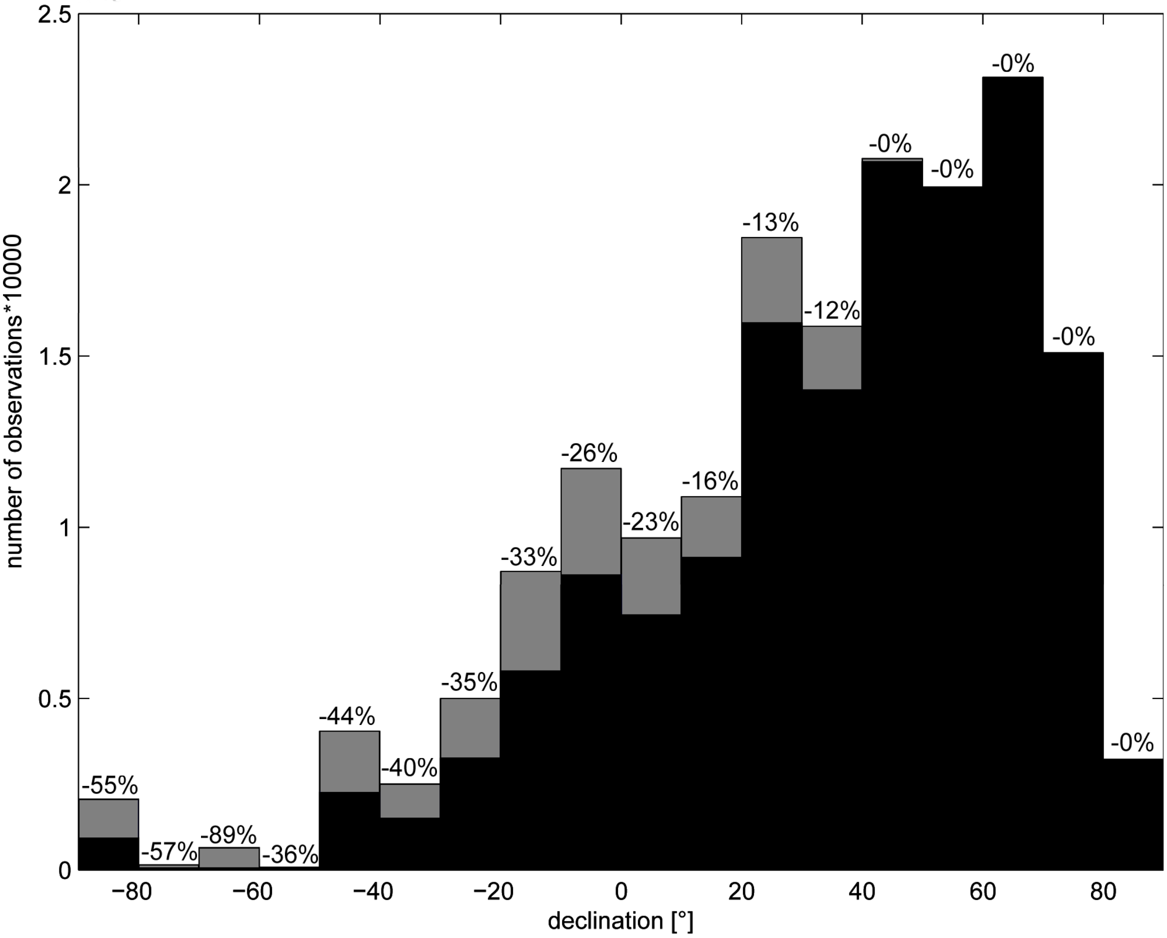

Figure 5.3: Source observations of the IVS-R1 network divided into 10° declination intervals once with and once without HartRAO. A loss of observations is depicted in grey. The percentage value of the observation loss is also provided.

observation data was created using a simulator.

5.2 Network volume

Malkin (2009) suggests that the network volume is connected to precision (formal error) and accuracy (weighted root mean square error with respect to a reference EOP time series) through a power law depicted in Equation 5.1

$$\sigma = a \cdot V^c, \tag{5.1}$$

where σ is an EOP error, a and c are best fitted parameters. Equation 5.1 can be transformed into the linear form,

$$\log \sigma = b + c \cdot \log V, \tag{5.2}$$

where $b = \log a$. Using Equation 5.2 the parameters b and c are derived from a best fit regression model of the data; for their values see Malkin (2009).

The network size was calculated according to Malkin (2009). First, to compute a tetrahedron mesh, a Delaunay triangulation was carried out using Matlab. In a second step the volume of each tetrahedron was calculated using

$$\frac{|(\boldsymbol{r2} - \boldsymbol{r1}) \times ((\boldsymbol{r3} - \boldsymbol{r1}) \times (\boldsymbol{r4} - \boldsymbol{r1}))|}{6}, \tag{5.3}$$

where $\boldsymbol{r1}$, $\boldsymbol{r2}$, $\boldsymbol{r3}$, $\boldsymbol{r4}$ are the geocentric station vectors. A summation of all the tetrahedron volumes calculated with Equation 5.3 results in the total network volume.

The different sizes of VLBI networks are listed in Table 5.1, sorted from the smallest to the largest network volume. Also, to get a general idea, the smallest and largest VLBI network as well as the volume of the Earth are provided. Note that without HartRAO or TIGOCONC the network volume shrinks by about 32%.

The power law allows the prediction of EOP precision for different network sizes. Table 5.2 contains the predicted values for the CONT08 network, with and without HartRAO, as well as the difference expressed as a percentage. According to the power law the precision is degraded by up to 14% if HartRAO is removed. It has to be noted that the result of Equation 5.1 is an approximate value that only takes volume into account. In reality, parameters such as baseline orientation, station equipment etc. have to be considered as well. This approach, however, can be used as a first indicator for the importance of the station for EOP and can be used to compare different stations and their location.

Table 5.1: Volume of CONT08 VLBI network without particular stations and the reduction of the volume in %

Name	Volume [Mm^3]	[%]
Without TIGOCONC	181,04	67,3
Without HARTRAO	181,11	67,32
Without TSUKUB32	201,67	74,96
Without KOKEE	204,35	75,96
Without WESTFORD	205,66	76,45
Without NYALES20	249,58	92,77
Without ZELENCHK	251,67	93,55
Without MEDICINA	261,67	97,27
Without SVETLOE	268,39	9,73
Without ONSALA60	268,42	99,78
Without WETTZELL	268,97	99,98
All Stations	269,02	100
Earth	1083	
Biggest network T2043	487,1	
Smallest network JADE-0610	9,93E-04	

Table 5.2: Predicted precision for the CONT08 network, with and without HartRAO, using the power law by Malkin (2009).

	xpol [μas]	ypol [μas]	dut1 [μs]	nutdx [μas]	nutdy [μas]
with HartRAO	64	56	2,9	45	45
without HartRAO	74	65	3,4	49	49
Difference [%]	87.0	86.3	86.0	91	91.0

5.3 Formal error and repeatability of EOP

Hase (2010) showed that the formal error of EOP is a good measure for quantifying the importance of a VLBI station. In this section his method, which was used for the station TIGOCONC, will be extended and applied to the station HartRAO.

The CONT08 campaign includes 15 consecutive days and, therefore, 15 sessions. To evaluate the importance of a single station the 15 sessions have to be analysed with and without that specific station. The default parametrisation described in Chapter 4 was used for the analysis. In order to compare the sites that participated in CONT08 this method was used for every telescope in the network. Then formal errors are averaged and the standard deviation of the estimates is calculated over all 15 session. With this approach one can compare the importance of each station in the network for each EOP. This is only possible because the same network of stations is used in every one of the 15 sessions. As mentioned previously (Section 5.1) the results might be too pessimistic, since the removal of a station results in an imperfect schedule.

In Table 5.3 the mean (average of all 15 CONT08 sessions) values of the formal error of EOP (polar motion coordinates are denoted as xpol and ypol respectively, the rotation angle is denoted as dut1 and the nutation coordinated are denoted as nutdx and nutdy respectively) is listed. As shown in Section 5.2, the formal error of the EOP should get smaller when the network's geometry gets better (it's size increases). The smallest average formal error is achieved when all stations are considered. Therefore, this assumption can be confirmed by the data. In general, the data suggests that in particular remote stations (with respect to the majority of stations — in this case outside of Europe) are important for EOP estimation. This coincides with Section 5.2 since remote stations have a bigger impact on network volume.

Baselines with a high north-south extension are sensitive to polar motion (Nothnagel *et al.*, 1988). Therefore, in order to get a good estimation of polar motion coordinates, it is crucial to include stations in high and low latitudes. Results from the CONT08 campaign, seen in Table 5.3, confirm those findings. An exclusion of a station such as HartRAO (with many north-south baselines – mainly with Europe) results in a worse estimate for polar motion.

Long east-west baselines, on the other hand, are sensitive to the earth rotation angle dUT1. Therefore, if dUT1 is estimated, stations at different longitudes are essential. This circumstance can be clearly seen in the results listed in Table 5.3. The worst estimate for dUT1 is achieved when remote (in the sense of longitude) stations like TSUKUB32 and KOKEE are removed from the network. When the station KOKEE, which is located in Hawaii, is removed from the network the average formal error of dUT1 doubles.

The data from Table 5.3 suggests that HartRAO is of high importance for the y coordinate of polar motion (when HartRAO is excluded from the network the average formal error doubles). Results from Table 5.3 also imply that HartRAO is by far the most important station of the CONT08 network for nutation estimation.

The standard deviation (repeatability) of EOP estimates w. r. t. the a priori values (IERS 08 C04) is listed in Table 5.4. One can see that the best solution (smallest standard deviation) is not always obtained when all telescopes are observing which would be the case in an ideal world. This is due to the fact that some stations might have less accurate or corrupted data. However, the importance of HartRAO can be seen clearly. When HartRAO is excluded from the network the estimates for polar motion as well as nutation get worse. The standard deviation of the y-coordinate of polar motion and the x-coordinate of nutation almost triples when HartRAO is removed.

It has to be noted that the standard deviation as well as the average formal error was calculated from only 15 sessions and is, therefore, prone to outliers.

The data from the IVS-R1 sessions where HartRAO participated were used in a similar analysis. The main difference is that the IVS-R1 sessions do not have a consistent station network (the geometry changes). Therefore, the analysis can not be conducted for every station but only for one station (in this case HartRAO). The results are comparable with the CONT08 network since the same parametrisation was used for the analysis. In a similar manner, the data was processes once with and once without HartRAO. The results are too

Table 5.3: Formal error (average over all CONT08 sessions) of EOP estimated from the CONT08 campaign. Each line lists the changes in average formal error when the respective station (denoted in the first column) is excluded, e.g. "none" means no station was excluded, "HartRAO" means that the station HartRAO was excluded and so on. The largest mean formal error per parameter is highlighted with bold numbers.

Excluded stations	Average formal errors				
	xpol [μas]	ypol [μas]	dut1 [μs]	nutdx [μas]	nutdy [μas]
none	33.7	32.1	1.23	16.8	17.0
HartRAO	40.4	**68.5**	1.25	**23.2**	**24.4**
KOKEE	**54.4**	40.3	**2.58**	20.2	20.0
MEDICINA	34.8	32.3	1.25	17.2	17.4
NYALES20	36.5	34.4	1.37	18.5	18.7
ONSALA60	35.1	33.1	1.29	17.6	17.9
SVETLOE	35.4	33.8	1.33	17.8	18.1
TIGOCONC	43.5	35.3	1.02	20.7	20.9
TSUKUB32	44.6	35.2	1.98	18.4	18.7
WESTFORD	37.4	40.3	1.54	19.5	19.7
WETTZELL	37.0	34.6	1.35	18.4	18.6
ZELENCHK	33.9	32.2	1.24	17.1	17.3

Table 5.4: Standard deviation (over all CONT08 sessions) of EOP estimates from the CONT08 campaign. Each line lists the changes in standard deviation when the respective station (denoted in the first column) is excluded, e.g. “none” means no station was excluded, “HartRAO” means that the station HartRAO was excluded and so on. The largest standard deviation per parameter is highlighted with bold numbers.

Excluded stations	Standard deviation of estimated parameters				
	xpol [μas]	ypol [μas]	dut1 [μs]	nutdx [μas]	nutdy [μas]
none	92	58.6	19.5	26.1	38
HartRAO	117	**149.8**	18.8	**62.4**	**53.8**
KOKEE	88.4	91	**22.2**	32.7	39.7
MEDICINA	106.3	60.7	19.2	29.8	41
NYALES20	92.2	60.2	19.6	24.8	43.6
ONSALA60	94.8	65.2	19.7	27	41.3
SVETLOE	94.5	56.9	19.4	23.9	39.3
TIGOCONC	**123.3**	76.2	19.6	34.7	36.2
TSUKUB32	84	46	18	40.2	46.9
WESTFORD	105.3	74.4	19.8	28.8	47.5
WETTZELL	93.6	57	19.5	27.2	42.1
ZELENCHK	95.4	60.1	19.8	29.1	40.3

pessimistic due to imperfect schedules as mentioned in previous sections.

Figure 5.4 depicts the formal errors of the EOP calculated from the IVS-R1 network. The IVS-R1 session where HartRAO is included are illustrated in black; the same IVS-R1 sessions but with HartRAO excluded are depicted in grey. Similar to the analysis with the CONT08 network the results suggest that HartRAO is especially important for polar motion and nutation. In order to quantify the increase in formal error when HartRAO is excluded from the network, the percentage values of the increase of the formal error were calculated from each session and then averaged. The median (written in brackets next to the averaged percentage value) was calculated as well. When HartRAO is excluded from the IVS-R1 sessions the formal error of polar motion increases by 55% (52%) for the x-coordinate and by 142% (124%) for the y-coordinate. A clear increase can also be found in the formal error of nutation, the formal error of the x-coordinate increases by 55% (50%) and the y-coordinate by 60% (55%). The effects on dUT1 are not that predominant, only a small increase of 23% (0%) can be detected. The findings from the IVS-R1 session agree very well with the results from the CONT08 campaign.

In Figure 5.5 the estimates of the EOP w. r. t. the a priori values (IERS 08 C04) are depicted. Similar to the previous plot sessions with HartRAO are illustrated in black and sessions where HartRAO was excluded are depicted in grey. To get the repeatability of the estimates the standard deviation was calculated. Polar motion and nutation are again affected the most with an increase of the repeatability of 103% and 120% for the x-coordinate and y-coordinate of polar motion respectively and an increase of 37% and 122% for the x-coordinate and y-coordinate of nutation respectively. Only a small increase of 33% can be detected for dUT1.

5.4 Correlation

In this section, the correlation between EOP is discussed. With a lower correlation between EOP the separability improves; hence, the EOP are better defined. As a result of the “No Net Translation” and “No Net Rotation” approach the EOP are also correlated with the station coordinates. Consequently, the station coordinates must also be taken into account. In Figure 5.6 the mean correlation matrix of all sessions of the CONT08 project is illustrated. The upper matrix was derived using all the stations of the network. In the lower one HartRAO was excluded from the estimation process. For better readability, the EOP are drawn in double size.

One can see that an exclusion of HartRAO does not make much of a difference when only the correlation between EOP is taken into account. The correlation might even become less between some parameters (see correlation between ypol and dut1). But in order to understand and quantify the importance of a station the whole matrix has to be studied. Overall, the correlation matrix, where HartRAO was dismissed, has much darker spots and, hence, has a higher correlation than the one with all the stations in it. In particular, the

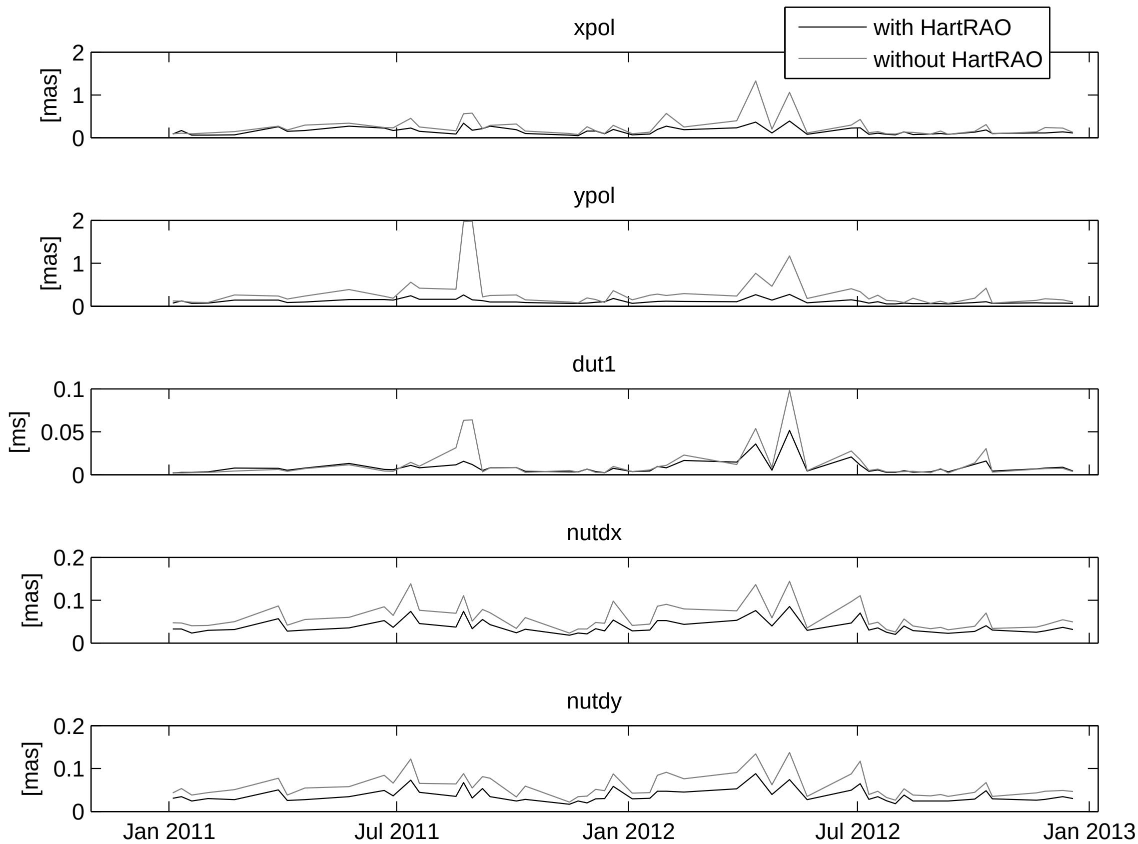

Figure 5.4: Formal error of the EOP estimated from IVS-R1 sessions once analysed with and once without the station HartRAO.

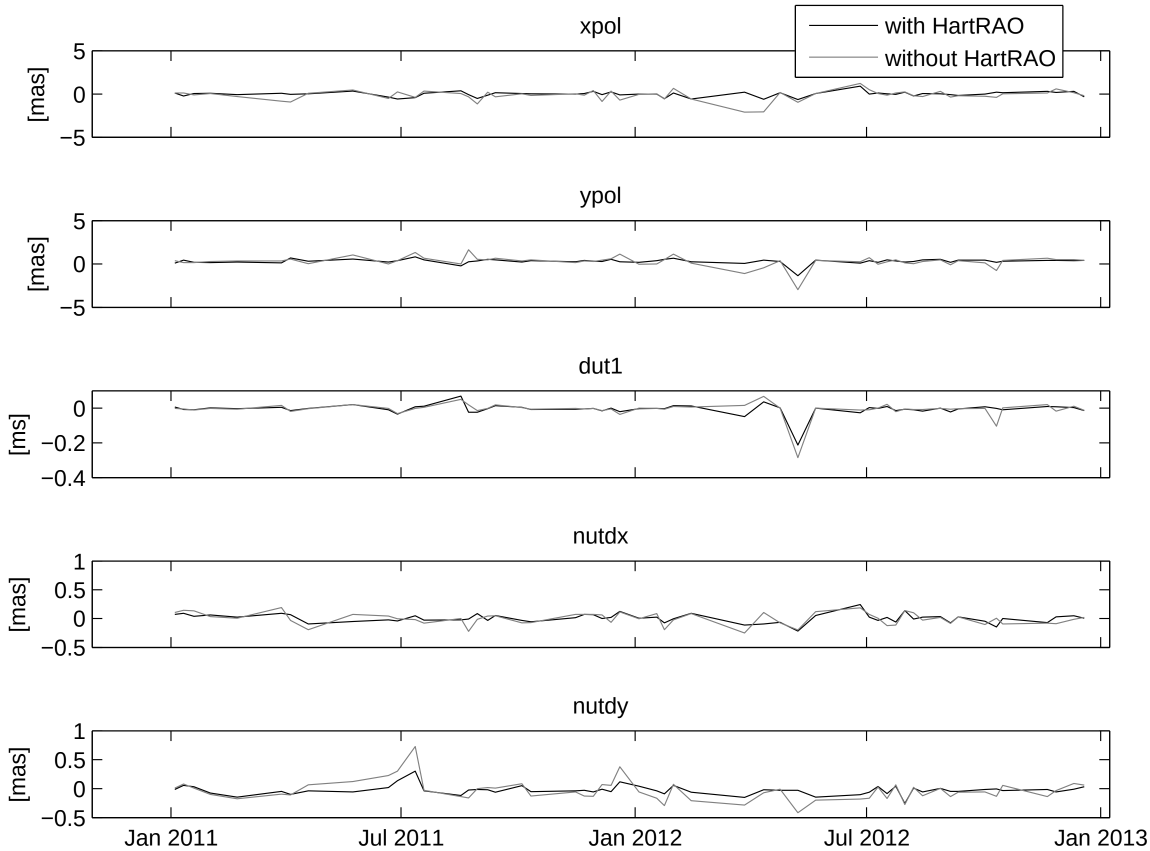

Figure 5.5: EOP estimates w.r.t. IERS 08 C04 series from the IVS-R1 sessions once analysed with and once without the station HartRAO.

correlation between EOP and coordinates is much less with HartRAO in the network. The correlation between different stations becomes higher if HartRAO is excluded as well. To visualise the change in the correlation values a third plot was created, see Figure 5.7. It depicts the difference between the absolute correlation values of the two network solutions (the network with HartRAO removed was subtracted from the normal CONT08 network). Positive values indicate that the correlation improves and negative values indicate that the correlation degrades when HartRAO is removed. The results suggest that HartRAO is of lower importance for dUT1 but is of high importance for the other four EOP.

In order to investigate and somehow quantify the change of correlation the matrix was divided into three parts and the absolute correlation values of each submatrix were summed up. This was done for the network with and without HartRAO. Following changes in correlation can be observed:

- correlation between EOP – with HartRAO: 1.18; without HartRAO: 1.31,
- correlation between coordinates – with HartRAO: 59.69; without HartRAO: 71.21 and
- correlation between EOP and coordinates – with HartRAO: 14.41; without HartRAO: 17.97.

One can see that, when HartRAO is excluded from the network, the overall correlation becomes higher. The smallest increase (about 10%) can be observed between the EOP. Between coordinates the correlation increases by approximately 16%. The correlation between EOP and coordinates has the biggest increase of about 20%.

A similar analysis was done for the IVS-R1 data set. The main difference is that the network geometry changes; therefore, it would not be fair to compare the correlation between coordinates for the whole data set. However, the correlation between EOP can be compared. In Figure 5.8 the correlation between all EOP for each session is depicted. Similar to the previous analysis HartRAO was once kept in the data (black line) set and once excluded (grey line).

Figure 5.8 clearly depicts a systematic: All correlations with one of the nutation coordinates are very small. This can also be observed in Figure 5.6. However, the correlation between polar motion and polar motion and dut1 is significant. When HartRAO is excluded from the data set the correlation between the x and y coordinate of polar motion increases by 24 %, the correlation between x coordinate of polar motion and dut1 increases by 83 % and the correlation between y coordinate and dut1 decreases by 15 %.

Drawing conclusion from parts of the correlation matrix is rather difficult if not impossible. The reason for the partly increase and decrease of correlation is not known and in order to provide a reasonable conclusion further research is necessary.

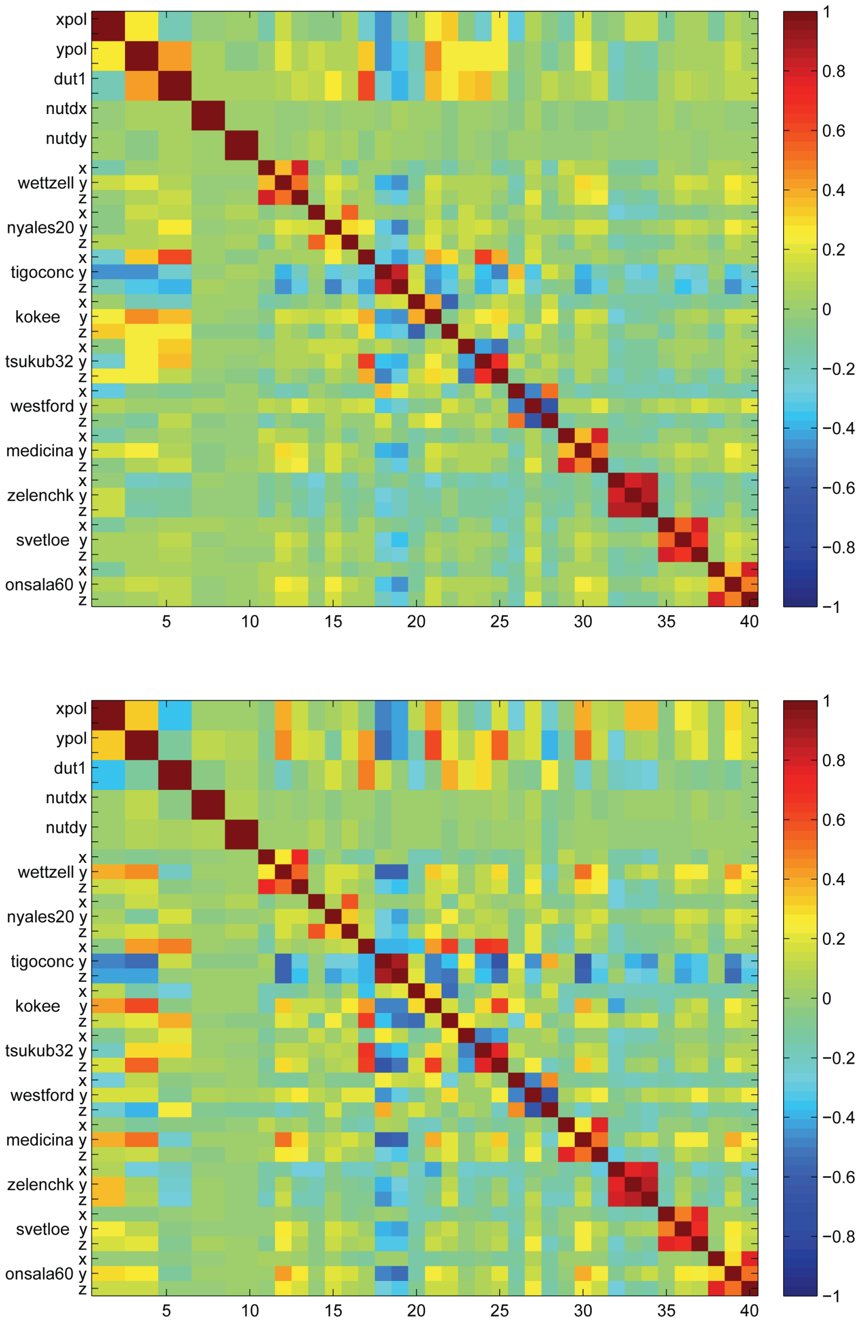

Figure 5.6: Mean correlation matrices of all sessions of the CONT08 project estimated once with (upper plot) and once without (lower plot) HartRAO. Both axis should have the same labels; however, the horizontal axis was changed to a number code (e.g. the x coordinate of Wettzell is equal to the entry 11) for a better readability.

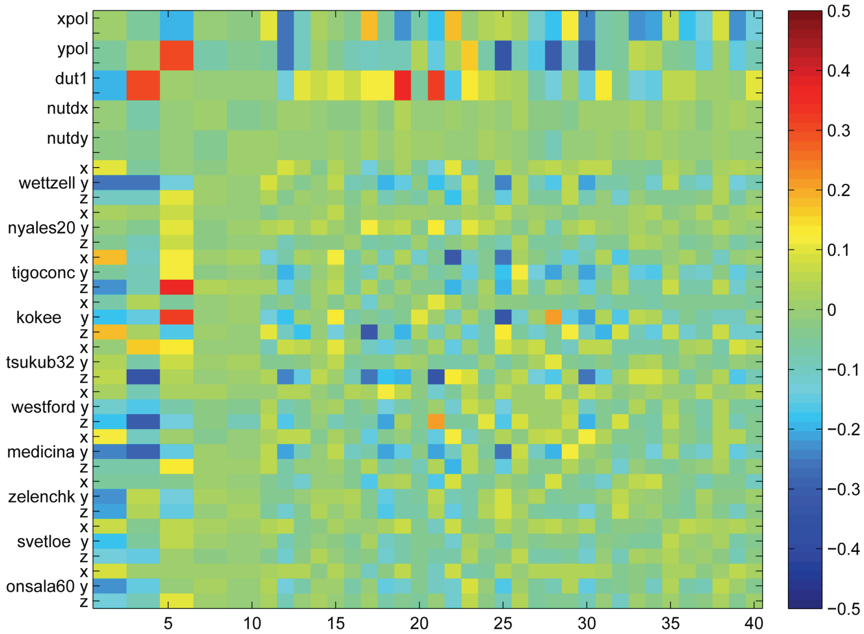

Figure 5.7: Difference between mean correlation matrices of all sessions of the CONT08 project estimated once with (upper plot) and once without (lower plot) HartRAO. Both axes should have the same labels; however, the horizontal axis was changed to a number code (e.g. the x coordinate of Wettzell is equal to the entry 11) for a better readability.

5.5 Baseline length repeatability

One of VLBI's major products is the TRF; therefore, the estimation of station coordinates has high priority. A measure for the quality of estimated station coordinates is the baseline length scatter (baseline length repeatability). It is especially important since it is independent from Earth's rotation. In the further analysis the data from the CONT08 campaign and IVS-R1 sessions is processed once with and once without HartRAO, then the baseline length scatter is examined. These plots depict the weighted standard deviation (repeatability) of baselines in the network. As a weight the square of the inverse formal error per baseline was used. Baselines with less observations have higher formal errors, hence, a lower weight. Therefore, the weighting procedure accounts for an accuracy loss due to less observations. On the x-axis the mean average baseline length and on the y-axis the weighted standard deviation is plotted. A linear trend, which resembles the station movement, was removed before calculating those values.

Figure 5.9 depicts the baseline length scatter of the CONT08 experiment. It was calculated once with and once without HartRAO. As a general rule, one can say that longer baselines are more affected (up to approximately 5 mm) from an exclusion of HartRAO. Smaller baselines (mainly in Europe) experience almost no changes. Baselines with the station TIGOCONC (dots in the upper right corner) are particularly affected by a removal of HartRAO. This is due to the fact that TIGOCONC is an isolated (in a global sense) station in South America

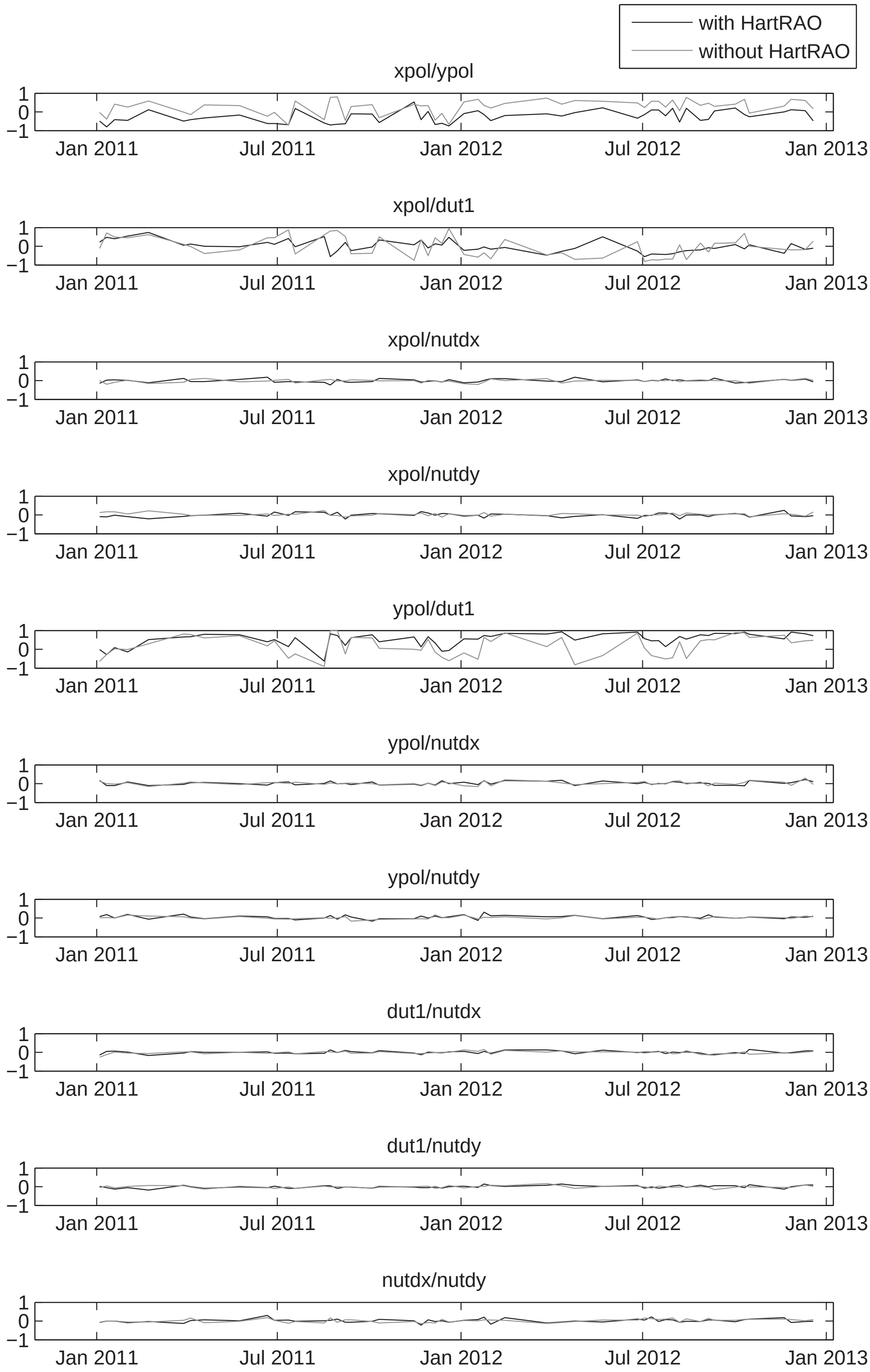

Figure 5.8: Correlation between all 5 EOP estimated once with (black line) and once without (grey line) HartRAO for all IVS-R1 sessions between beginning of 2011 until end of 2012 where HartRAO participated.

and has many observations together with HartRAO.

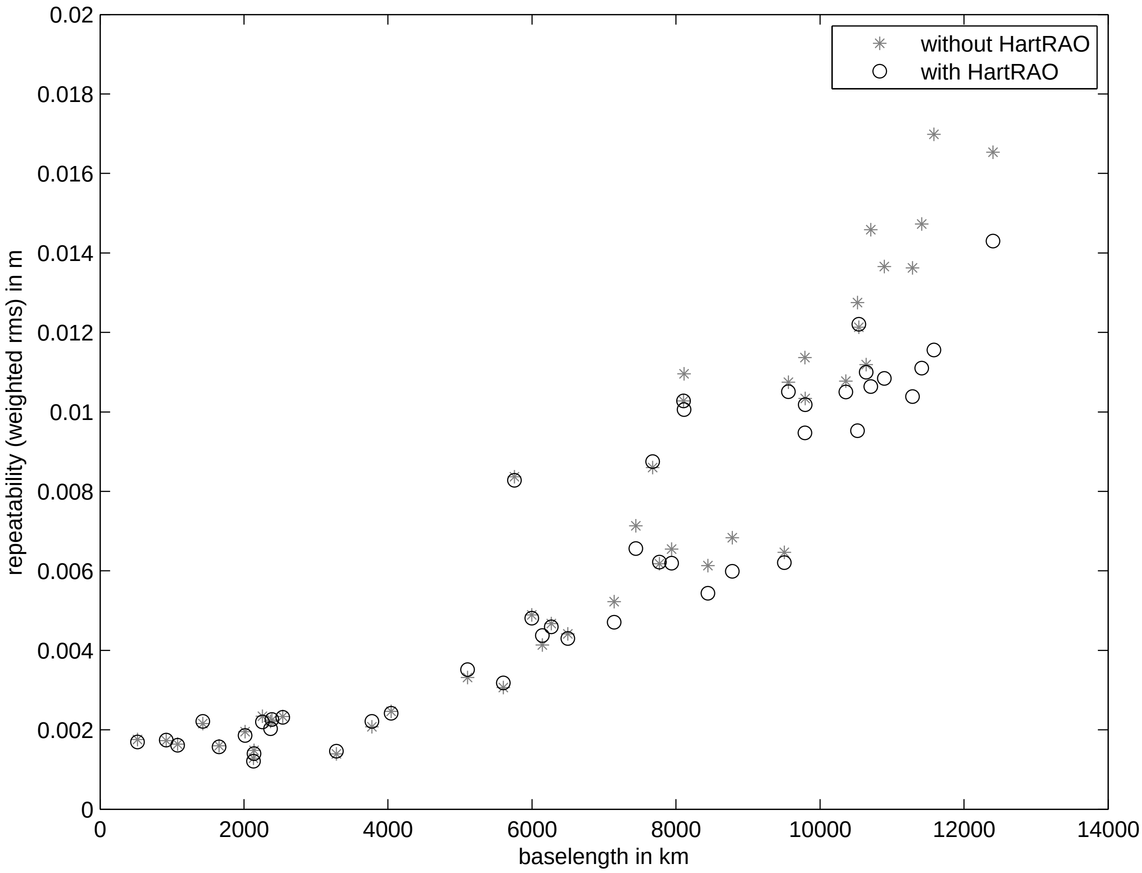

Figure 5.9: Baseline length repeatability (weighted rms) plot of the CONT08 network, with and without HartRAO.

A similar analysis was conducted for the IVS-R1 data, it is depicted in Figure 5.10. The data was processed once with and once without HartRAO. The data suggests that HartRAO has, similar to the results from the CONT08 experiment, almost no effect on shorter baselines but affects longer baselines. This is due to the fact that longer baselines are tendentially baselines to remote stations. Therefore, one can conclude that HartRAO is of high importance for other remote stations. In particular, the station TIGOCONC is, similar to the results from CONT08 experiment, highly dependent on HartRAO. Since the network in this data set varies not all baselines occur equally often, a selection has to be made. Baselines which are calculated at least 5 times (higher thresholds were considered as well but delivered similar results) were considered. The data set was corrected for station drift and for the earthquake in Japan (March 11, 2011).

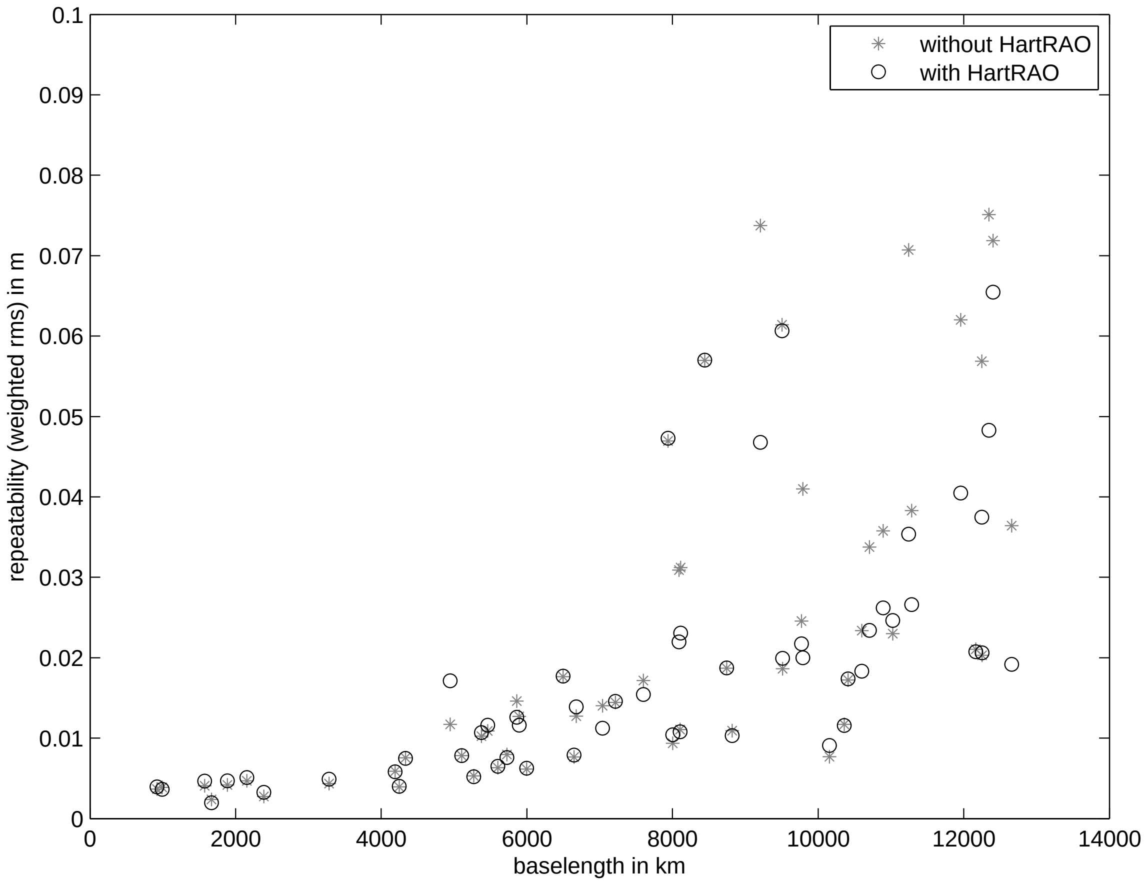

Figure 5.10: Baseline length repeatability (weighted rms) plot of the IVS-R1 sessions of the year 2011 and 2012 with and without HartRAO.

Chapter 6

Evaluating the importance of the HartRAO station for the future VLBI network

In this chapter the importance of HartRAO for the future network is evaluated using simulated data. Some of the results presented in this chapter have been published previously by the author, see Mayer *et al.* (2014).

6.1 Number of observations

Since the session was rescheduled each time a new telescope was placed at HartRAO the number of observations can be used as a first measure of quality of the schedule and, therefore, as a measure of importance of the telescope at HartRAO.

In Table 6.1 the total number of scans and observations of the VGOS network with different telescopes at HartRAO is listed. It can be seen that by placing the telescope Hart15 at HartRAO only a small improvement (compared to the network without HartRAO) in the overall number of observations and number of scans is achieved. This is due to the slow slew speed of the Hart15 antenna, other fast slewing antennas might have to wait for the slower one and, therefore, lose observations. However, these results do not indicate that the Hart15 telescope is of lesser benefit to the VGOS network. In this particular case the advantage of a better geometry prevails the small increase in station observations, see Section 6.4. If the telescope Hart2010 is placed at HartRAO a significant increase in the number of observations and number of scans can be observed. An even better result can be achieved by placing a twin telescope (HartTWIN) at HartRAO.

In Figure 6.1 the number of observations per station for the VGOS network with different telescopes placed at HartRAO is depicted. Stations that benefit mostly from an upgrade of the HartRAO station are FORT2010, CNAR2010 and YEBE2010. The results suggest

Table 6.1: Number of scans and observations for the VGOS network with different Telescopes places at HartRAO

	Without HartRAO	Hart15	Hart2010	HartTWIN
Number of scans	9840	9886	10153	10332
Number of observations	92453	93918	100355	107169

that most of the other stations in the network would experience a decrease in the number of observations if Hart15 participates in the session. This is again due to the reason mentioned previously and is not an indicator that introducing Hart15 yields a worse result. An upgrade to Hart2010 or HartTWIN, on the other hand, yields a higher number of observations for almost every station. Because of its remote location HartRAO has the smallest number of observations (8100 obervations) even if a VGOS antenna is placed at the site. The best result is achieved if HartTWIN is included in the experiment. One can also see that the number of observations per station is much higher north of the Equator which is due to the uneven distribution between Northern and Southern Hemisphere.

It has to be noted that comparing the number of scans and observations is only a rough estimation of the quality of a scheduled network. However, in this case this measure can be used to get a quick idea of the importance of a station on the schedule.

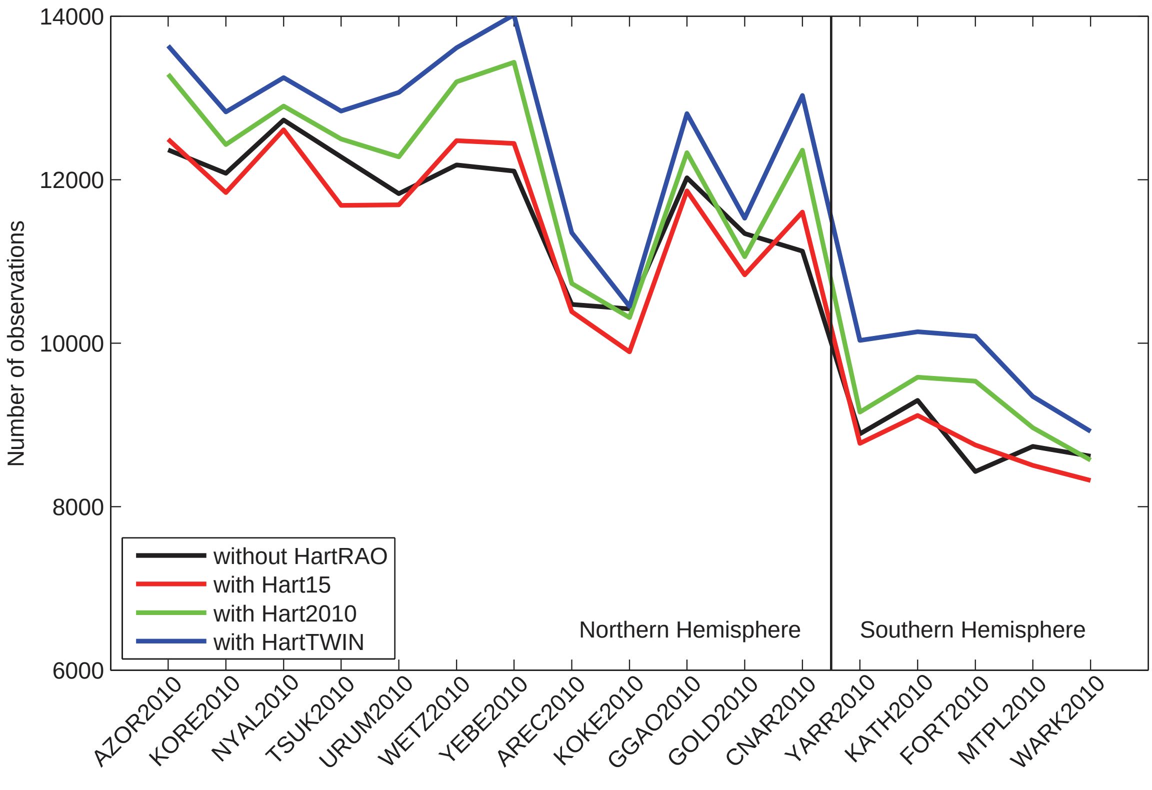

Figure 6.1: Number of observations per station for the four different VGOS networks.

6.2 Contribution to the ICRF

The contribution of different telescopes placed at HartRAO to the ICRF is discussed on the basis of comparing the number of observations to sources. A priori coordinates of sources used to schedule and process these sessions are taken from the ICRF2 catalog.

In order to get a good overview of the distribution of the source observations over the declination a histogram was created (using a 10° increment) for each network solution. The histograms are then compared and analysed. This method is similar to the one used in Section 5.1.

Figure 6.2 depicts all histograms for all sessions and the comparison between them. The figure is structured in an upper triangular matrix form, where the four diagonal histograms illustrate the network solutions with different telescopes. In the other six entries a comparison of each network solution is provided. With this system one can immediately see the influence of a telescope upgrade, e.g. one is interested in the change of source observations for an upgrade from Hart15 to HartTWIN, the relevant histogram can be found in the fourth column of the second row. An increase of observations from an inferior to a better telescope (with "without HartRAO" being the worst to "HartTWIN" being the best) is depicted in green, a decrease in red. One can see the gradual improvement that comes with better telescopes. In general, the sources on the Southern Hemisphere benefit more from a telescope upgrade at HartRAO.

To see how HartRAO affects source observation in the Southern Hemisphere all observations are summed up and compared against the Northern Hemisphere. Figure 6.3 illustrates this comparison, the solution of the network with HartTWIN is taken as a reference and the others are in relation to it. The sources in the Southern Hemisphere benefit from an upgrade at HartRAO, in particular, an upgrade from Hart2010 to HartTWIN yields 8.3% more observations. Sources in the Northern Hemisphere also benefit from an upgrade to Hart2010 or HartTWIN, only an upgrade to Hart15 reduces the number of observations a little.

Upgrading the telescope at HartRAO always yields better results for observations on the Southern Hemisphere. The best results can be achieved by implementing a twin telescope at HartRAO.

6.3 Network volume

To get an idea of the importance of each station for EOP estimation the network volume approach suggested by Malkin (2009) is examined. This model was derived empirically using previous sessions of the old network. The new network, however, will include new stations, analysis strategies, observations techniques etc.; hence, one cannot use the empirically derived model to estimate accuracy and precision of EOP derived with the VGOS network. However, the relation between network volume and precision and accuracy of the EOP still applies. Therefore, comparing different network volumes is a good indicator for EOP quality. Table 6.2 lists the different network sizes as well as the percentage of volume loss (with respect to

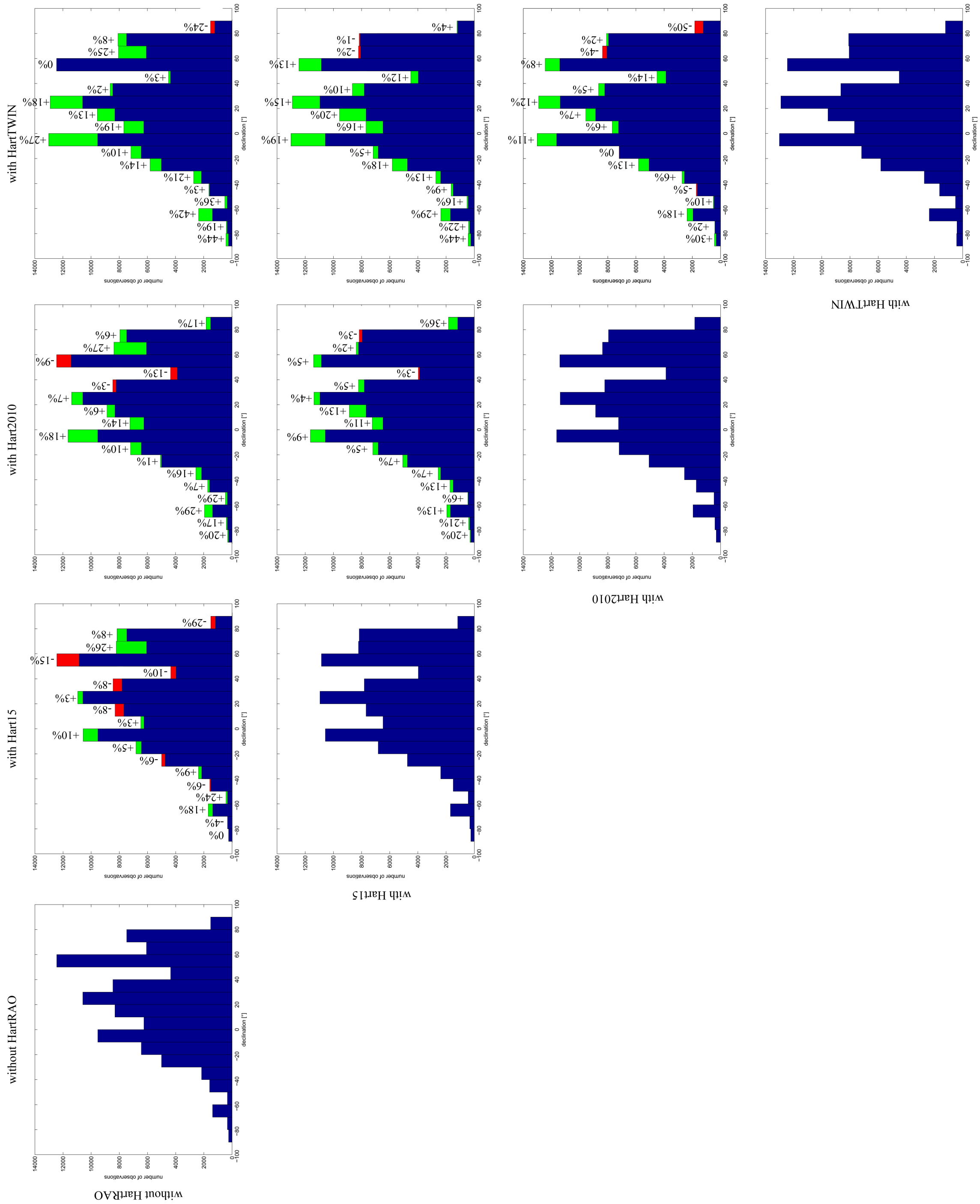

Figure 6.2: Histogram of source observations of the four different VGOS networks.

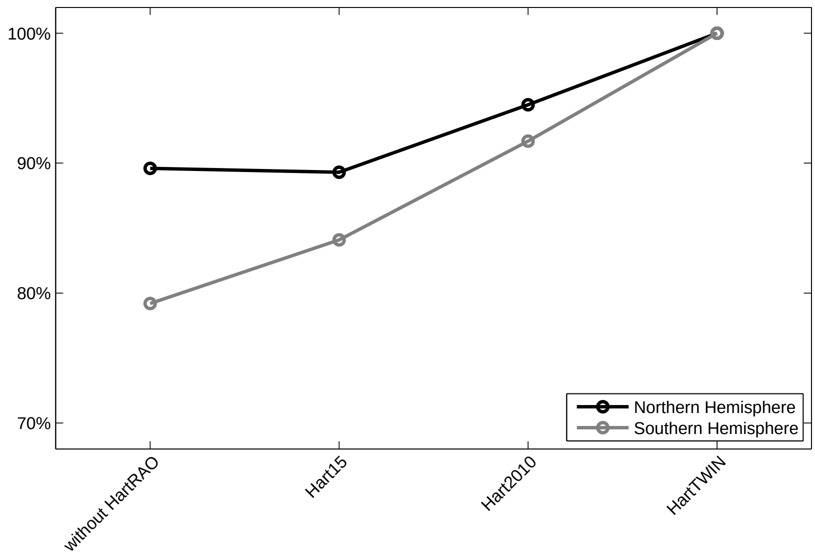

Figure 6.3: Comparison of number of observations to sources on the Northern and Southern Hemisphere.

the whole network with 18 stations) for each excluded station. The impact of HartRAO on the network volume (19.6%) is by far (the second biggest is Fortaleza with 7.6%) the largest. From these numbers one can conclude that HartRAO is of highest importance for precision and accuracy of the EOP. This result yields that, if only network geometry is considered, HartRAO is the most important stations of the VGOS network.

6.4 Formal error of EOP

In Figure 6.4 the formal error of the EOP for different telescopes at HartRAO is depicted. To get a better understanding of the behavior of the error, the solution of the VGOS network with HartTWIN (since it yields the lowest formal errors) was set as a reference and all other results are plotted as percentage values w. r. t. this network, e.g. the x-coordinate of polar motion of the VGOS network with no telescope at HartRAO has a 40 % higher formal error than the network with HartTWIN. The results suggest that a better telescope yields more accurate EOP, in particular polar motion and nutation is affected by the type of telescope placed at HartRAO. This coincides with the findings from Chapter 5. It is also important to notice that the by far largest formal errors are reached when no telescope is placed at HartRAO. This result coincides with the findings from Section 6.3, it suggests that the remote location of HartRAO makes it a crucial site for EOP estimation.

The average EOP estimates are around zero, which indicates that the simulation process was successful. In order to keep consistency with the methodology used in Chapter 5 the standard deviation of the estimates should also be compared, though it is not very meaningful,

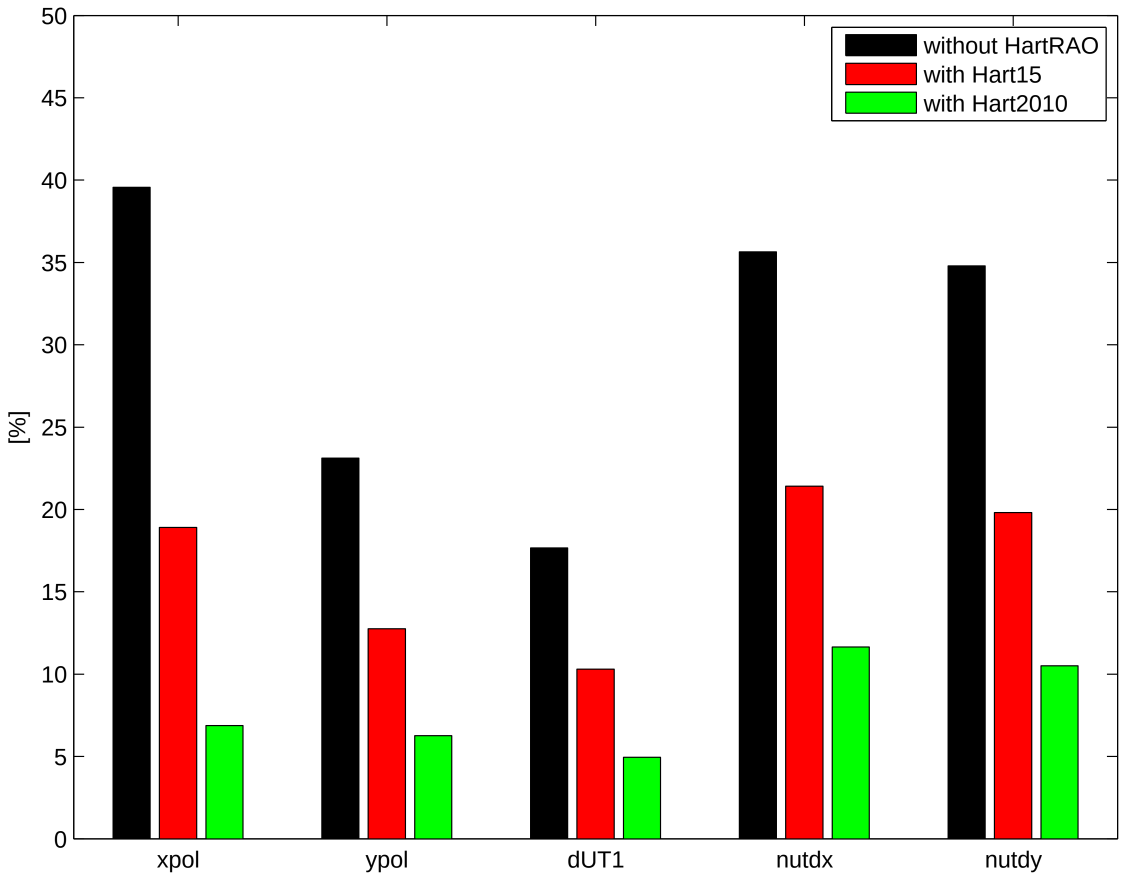

Figure 6.4: Increase (in percentage) of average formal error of EOP when the VGOS network is fitted with different telescopes (Hart15, Hart2010 and with no telescope at Hartebeesthoek). The ideal case, e.g. the network with HartTWIN is chosen as a reference (zero line).

Table 6.2: Different network volumes of the VGOS network and the reduction of the volume in %

Name	Volume $[Mm^3]$	[%]
Without HartRAO	415.68	19.6
Without FORTLEZA	477.52	7.6
Without URUMQI	478.68	7.4
Without WARKWORT	480.24	7.1
Without NYALES20	482.14	6.7
Without KOKEE	490.31	5.1
Without YARRA12M	498.49	3.6
Without GOLD2010	503.10	2.7
Without ARECIBO	503.31	2.6
Without KATH12M	505.90	2.1
Without GGAO2010	509.86	1.4
Without MT PLSNT	509.87	1.4
Without TSUKUB32	511.00	1.1
Without WETZ2010	511.10	1.1
Without CNARY IS	512.20	0.9
Without AZOR2010	512.46	0.9
Without KOREA	514.67	0.4
Without YEBE2010	516.05	0.2
All Stations	516.88	0.0

since it only depends on the simulation parameters and number of sessions that were simulated. Therefore, no such comparison was conducted.

6.5 Correlation

The correlation between parameters is discussed in this section. Table 6.3 lists the summed up (between similar parameters, e.g. EOP) absolute values from the correlation matrix, this method is similar to the one in Section 5.4. The values are miniscule and not of great significance. These results suggest that the decorrelation of parameters works perfectly fine even when HartRAO is excluded from the network. This is due to the fact that the network is rather large (18 Stations). In a big network, such as the one presented here, the dismissal of a station does not affect the correlation between parameters much. It has to be noted that the results would be significantly different for a smaller network, as discussed in Chapter 5.

6.6 Baseline length repeatability

In this section the baseline length repeatability of the VGOS network without HartRAO, with Hart15, with Hart2010 and with HartTWIN is discussed. In Figure 6.5 the four different solutions are depicted. A quadratic trend was fitted to each data set to provide an easy visual comparison. The result suggests that there is no significant difference between these solutions.

Table 6.3: Correlation (summed up absolute value) between EOP, between coordinates and EOP and between coordinates

	Correlation between EOP	Correlation between coordinates and EOP	Correlation between coordinates
Without HartRAO	0.06	0.05	0.09
Hart15	0.04	0.04	0.09
Hart2010	0.04	0.04	0.09
HartTWIN	0.04	0.05	0.09

Therefore, it can be concluded that no matter what telescope is placed at HartRAO, even if HartRAO is not participating in the network, the other coordinates are stable and not affected. This is not surprising, since the discussed network is rather large (18 stations) and, therefore, each station has enough baselines to estimate site coordinates with sufficient accuracy.

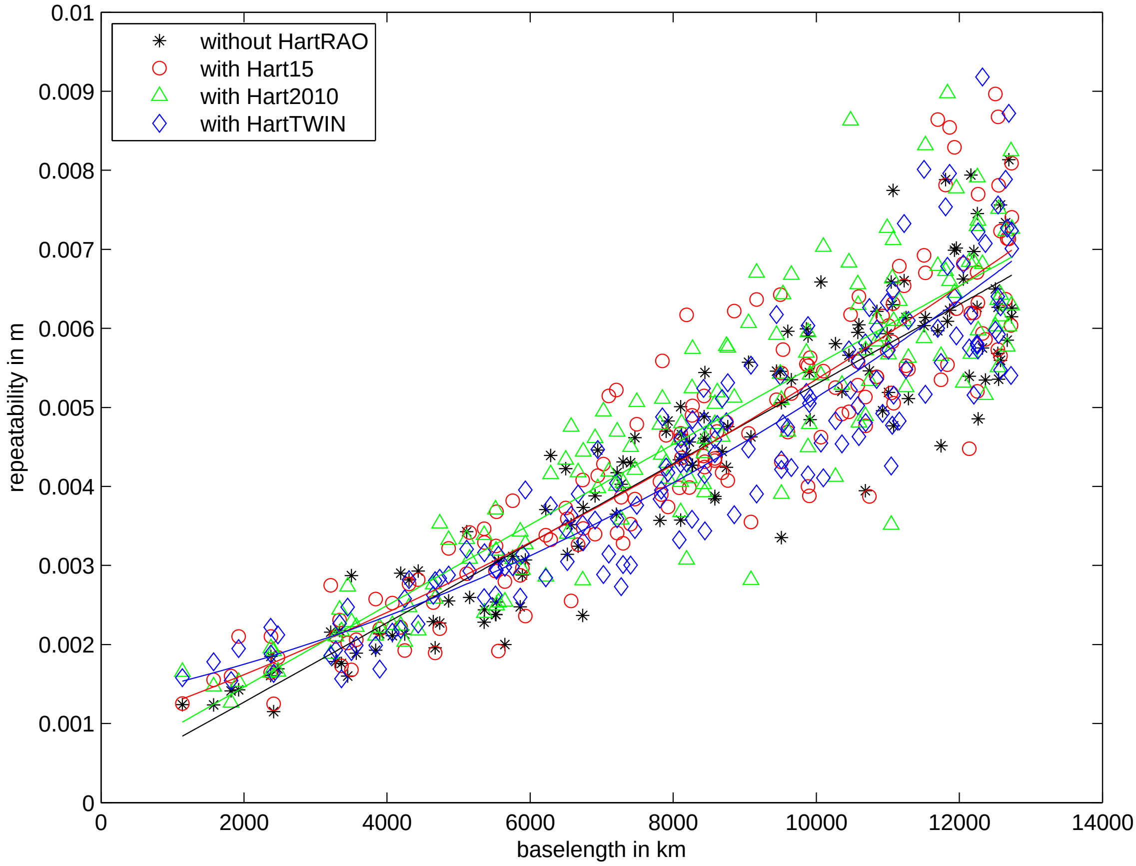

Figure 6.5: Baseline length repeatability plot of the VGOS network without HartRAO, with Hart15, with Hart2010 and with HartTWIN. A quadratic polynomial was fitted to each data set.

6.7 Station vector repeatability

The station vector repeatability is a measure of the stability of the station coordinate estimates. To get this measure the standard deviation over all 25 simulated sessions of the estimated station vector was computed for each station. The station vector repeatability was calculated for each network configuration (VGOS network with Hart15, Hart2010, HartTWIN and without HartRAO), it is depicted in Figure 6.6. It can be seen that the station vector repeatability stays more or less the same (changes are below the simulated errors and are therefore not visible) no matter what network configuration is used. The results indicate that no matter what telescope is placed at HartRAO the effect on the coordinates of other stations is negligible which means that the network is stable even if HartRAO is removed. This coincides with the findings in Section 6.6.

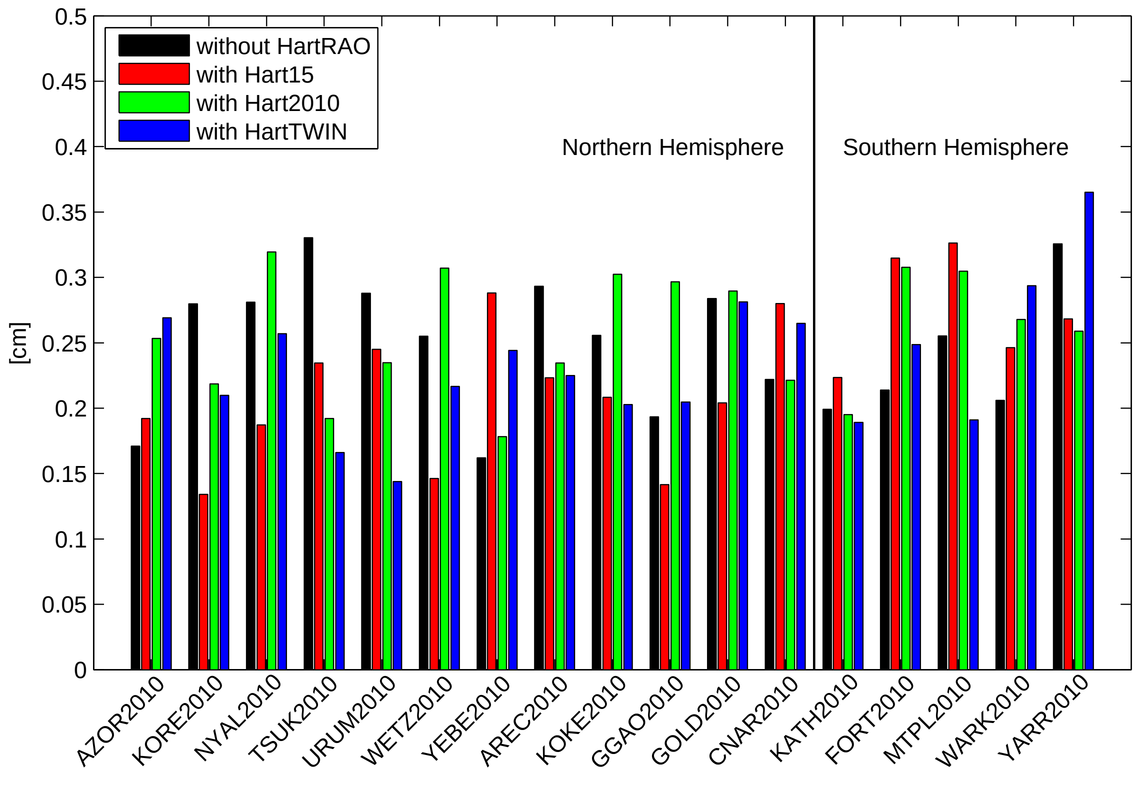

Figure 6.6: Station vector repeatability plot of the VGOS network without HartRAO, with Hart15, with Hart2010 and with HartTWIN.

In Table 6.4 the station vector repeatability of the station HartRAO is listed. It was calculated with three different telescopes (Hart15, Hart2010 and HartTWIN) at Hartebeesthoek. The results are not that clear, with the worst result being achieved when Hart2010 is placed at the site. This suggests, similarly to the results maintained from the other stations, that the changes are below the simulated error.

Table 6.4: Station vector repeatability of the station HartRAO evaluated with different telescopes placed at Hartebeesthoek

	Hart15	Hart2010	HartTWIN
Station vector repeatability [mm]	2.4	3.2	1.8

Chapter 7

Conclusion

In order to quantify the significance of the station HartRAO for the VLBI products (ICRF, ITRF and EOP) different analysis strategies, such as number of observations to radio sources, formal errors, correlation and baseline length repeatability were examined. This was done on the basis of different real data sets (CONT08 experiment and IVS-R1 sessions of the years 2011 and 2012) and artificial data sets (VGOS network with different telescopes, namely Hart15, Hart2010 and HartTWIN, placed at Hartebeesthoek). The real data sets were processed once with HartRAO (nothing was changed in the data set) and once without HartRAO (HartRAO was removed beforehand) and the difference was analysed. This approach has the disadvantage that the station is only excluded from the schedule which results in a non-optimal schedule. Therefore, results from real data are too pessimistic and have to be interpreted with that in mind. Artificial data is superior in this respect since it can be rescheduled each time a station is removed or a different telescope is placed at a site but the observations are simulated and, therefore, do not consider all error sources. The overall results suggest that HartRAO is of crucial importance for EOP estimation and the station network on the Southern Hemisphere.

To evaluate the importance of HartRAO for the ICRF the contribution of the station to observations to sources is examined. Since HartRAO is one of the few stations on the Southern Hemisphere, removing it would result in a loss of observations to southern sources. The outcome from the two real data sets suggest that sources with higher southern declination are especially affected with 35 % loss of observations to sources on the Southern Hemisphere for the IVS-R1 data set. Similar results are obtained from the simulated data set. The better the telescope the more observations to southern sources are achieved in the schedule. In particular, an upgrade from Hart2010 to HartTWIN results in 8.3 % more observations to sources on the Southern Hemisphere.

The impact of HartRAO on the EOP quality was examined based on formal errors and repeatabilities of estimates. Real data sets (CONT08 and IVS-R1) were analysed with and without HartRAO. The results suggest that HartRAO is one of the most important stations for the estimation of polar motion and nutation (with an increase of up to 50% and 50% to 100% for nutation and polar motion respectively). Artificial data were analysed in a similar manner. Results from the simulated data suggest that even an inferior telescope such as Hart15 yields a much better estimation of EOP than no telescope at Hartebeesthoek. Therefore, the advantage of a remote station such as HartRAO for EOP estimation prevails the loss of observations due to an inferior telescope. The average formal error of EOP steadily decreases (in particular for polar motion and nutation) when a superior telescope is placed at the site.

The importance of HartRAO for station coordinate estimation was evaluated using baseline length repeatability plots. Excluding HartRAO from the real data sets results in a worse estimation of station coordinates, especially for remote stations (short baselines are almost not influenced). In particular, baselines with the station TIGOCONC are heavily dependent on HartRAO with a repeatability up to 5 mm larger. The data from the artificial VGOS network suggest that excluding HartRAO does not affect other baselines. This is due to the fact that the VGOS network consists of 18 stations and is very stable, even when a station is dropped from the network.

Another parameter that can be examined in order to evaluate the importance of a station is the correlation between EOP and coordinates. It is not easy to interpret the change in correlation when a station is dropped from the network since the whole matrix has to be taken into account. However, as a general rule one can say that when HartRAO is removed from the real data set the correlation between parameters such as EOP and station coordinates gets higher. No effect can be identified in the simulated date set which suggests that the correlation of a large network, such as the presented VGOS network, is not influenced by the removal of a single station.

HartRAO is one of the most important stations in the current VLBI network and contributes significantly to the ICRF, ITRF and EOP. Furthermore, HartRAO will be one of the key stations in the new VGOS network and upgrading it will be of high priority for achieving the aim of mm accuracy. A failure of HartRAO results in a significant loss of EOP quality; therefore, it would make sense to have two telescopes at HartRAO or to increase the density of VLBI sites on the Southern Hemisphere, in particular in Africa.

The presented methodology can be used for other stations and networks and can be used to provide evidence to decision makers.

Abbreviations

ASD Allan Standard Deviation
CONT08 Continuous VLBI Campaign 2008
CRF Celestial Reference Frame
DORIS Doppler Orbitography and Radiopositioning Integrated by Satellite
dUT1 Delta Universal Time No. 1
e-VLBI electronic Very Long Baseline Interferometry
ENU East North Up
EOP Earth Orientation Parameters
GGOS Global Geodetic Observing System
GNSS Global Navigation Satellite Systems
GPS Global Positioning System
GSFC Goddard Space Flight Center
GUI Graphical User Interface
Hart15 HartRAO 15 m telescope
Hart2010 HartRAO VGOS telescope
HartRAO Hartebeesthoek Radio Astronomy Observatory
HartTWIN HartRAO twin telescope
ICRF International Celestial Reference Frame
IERS International Earth Rotation Service
IGG Institute of Geodesy and Geophysics
ITRF International Terrestrial Reference Frame
IVS-R1 International VLBI Service for Geodesy and Astrometry Rapid Turnaround 1 session
IVS International VLBI Service for Geodesy and Astrometry
NASA National Aeronautics and Space Administration
NNR No Net Rotation
NNT No Net Translation
O-C Observed minus Computed
RMS Root Mean Square
SEFD System Equivalent Flux Density
SKA Square Kilometer Array
SKED Scheduling Software

SLR Satellite Laser Ranging
SNR Signal to noise ratio
TIGOCONC Transportable Integrated Geodetic Observatory Concepcion
TIGO Transportable Integrated Geodetic Observatory
TRF Terrestrial Reference Frame
VCS Very Long Baseline Array Calibrator Survey
VGOS VLBI2010 Global Observing System
VIE_GLOB Vienna Global Solution Module
VIE_INIT Vienna Initialising Module
VIE_LSM Vienna Least Squares Matching Module
VIE_MOD Vienna Modeling Module
VIE_SCHED Vienna Scheduling Module
VIE_SIM Vienna Simulating Module
VieVS Vienna VLBI Software
VLBA Very Long Baseline Array
VLBI Very Long Baseline Interferometry
VTRF VLBI Terrestrial Reference Frame

List of Figures

List of Tables

Bibliography

Altamimi, Z., Collilieux, X. and Métivier, L. (2011). ITRF2008: an improved solution of the international terrestrial reference frame. *Journal of Geodesy*, 85, 457–473.

Behrend, D. and Nothnagel, A. (2013). International VLBI Service for Geodesy and Astrometry (IVS). In *Report of the International Association of Geodesy 2011-2013 – Travaux de l'Association Internationale de Géodésie 2011-2013*, Vol. 38, 364–371.

Böhm, J., Böhm, S., Nilsson, T., Pany, A., Plank, L., Spicakova, H., Teke, K. and Schuh, H. (2012). The new Vienna VLBI Software VieVS. In *Proceedings of the 2009 IAG Symposium, Buenos Aires, Argentina*, Vol. 136, 1007–1011, International Association of Geodesy Symposia, 31 August - 4 September 2009.

Campbell, J. (2000). From Quasars to Benchmarks: VLBI Links Heaven and Earth. In *IVS 2000 General Meeting Proceedings*, 19–34, NASA/CP-2000-209893.

Fey, A., Gordon, D. and Jacobs, C. (2009). *The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry*. IERS technical note 35, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie.

Hase, H. (2010). Zur Bedeutung von TIGO zur Bestimmung des ITRF, der EOP, EUREF und GREF. Tech. rep., available at http://www.tigo.cl/documents/100127BedeutungTIGO.pdf.

Lovell, J., McCallum, J., Reid, P., McCulloch, P., Baynes, B., Dickey, J., Shabala, S., Watson, C., Titov, O., Ruddick, R., Twilley, R., Reynolds, C., Tingay, S., Shield, P., Adada, R., Ellingsen, S., Morgan, J. and Bignall, H. (2013). The auscope geodetic VLBI array. *Journal of Geodesy*, 87, 527–538.

Malkin, Z. (2009). On comparison of the Earth orientation parameters obtained from different VLBI networks and observing programs. *Journal of Geodesy*, 83, 547–556.

Mälzer, H. (1984). 5.2.3 Measurements on a global scale. In K. Fuchs and H. Soffel, eds., *Subvolume A*, Vol. 2a of *Landolt-Börnstein - Group V Geophysics*, 368–374, Springer Berlin Heidelberg.

Mayer, D., Böhm, J., Combrinck, L., Botai, J. and Böhm, S. (2014). Importance of the Hartebeesthoek Radio Astronomy Observatory for the VLBI network. *Acta Geodaetica et Geophysica*, 49, 313–325.

Nicolson, G. (1995). VLBI at the Hartebeesthoek Radio Astronomy Observatory. *Astrophysics and Space Science*, 230, 329–339.

Nothnagel, A., Nicolson, G.D., Schuh, H., Campbell, J., Cloppenburg, H. and Kilger, R. (1988). Radiointerferometric Polar Motion Determination Using a Very Long North-South Baseline. In A.K. Babcock and G.A. Wilkins, eds., *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*, Vol. 128 of *IAU Symposium*, 193.

Pany, A., Böhm, J., MacMillan, D., Schuh, H., Nilsson, T. and Wresnik, J. (2011). Monte Carlo simulations of the impact of troposphere, clock and measurement errors on the repeatability of VLBI positions. *Journal of Geodesy*, 85, 39–50.

Petit, G. and Luzum, B., eds. (2010). IERS Conventions 2010. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, IERS Technical Note No. 36.

Petrachenko, B., Niell, A., Behrend, D., Corey, B., Böhm, J., Charlot, P., Collioud, A., Gipson, J., Haas, R., Hobiger, T., Koyama, Y., MacMillan, D., Malkin, Z., Nilsson, T., Pany, A., Tuccari, G., Whitney, A. and Wresnik, J. (2009). Design Aspects of the VLBI2010 System. Progress Report of the IVS VLBI2010 Committee. Tech. rep., available at http://adsabs.harvard.edu/abs/2009vlbi.rept....1P.

Petrov, L. (1999). Steps towards phase delay VLBI. In *Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry*, 144–151.

Rogers, A.E.E. (1970). Very Long Baseline Interferometry with Large Effective Bandwidth for Phase-Delay Measurements. *Radio Science*, 5, 1239–1247.

Sasao, T. and Fletcher, A.B. (2011). Introduction to VLBI Systems. Tech. rep., available at http://www.ipa.nw.ru/smu/files/lib/kchap4.pdf.

Schuh, H. (2000). Geodetic Analysis Overview. In *IVS 2000 General Meeting Proceedings*, 219–229, NASA/CP-2000-209893.

Schuh, H. and Behrend, D. (2012). VLBI: A fascinating technique for geodesy and astrometry. *Journal of Geodynamics*, 61, 68 – 80.

Schuh, H. and Böhm, J. (2013). Very Long Baseline Interferometry for Geodesy and Astrometry. In G. Xu, ed., *Sciences of Geodesy - II*, 339–376, Springer Berlin Heidelberg.

Sovers, O.J., Fanselow, J.L. and Jacobs, C.S. (1998). Astrometry and geodesy with radio interferometry: experiments, models, results. *Reviews of Modern Physics*, 70, 1393–1454.

Sun, J., Böhm, J., Nilsson, T., Krásná, H., Böhm, S. and Schuh, H. (2014). New VLBI2010 scheduling strategies and implications on the terrestrial reference frames. *Journal of Geodesy*, 88, 449–461.