Master Thesis

Simulations of VLBI observations with the Onsala Twin Telescope

carried out in order to obtain the academic degree
“master of the technical sciences “
under the supervision of

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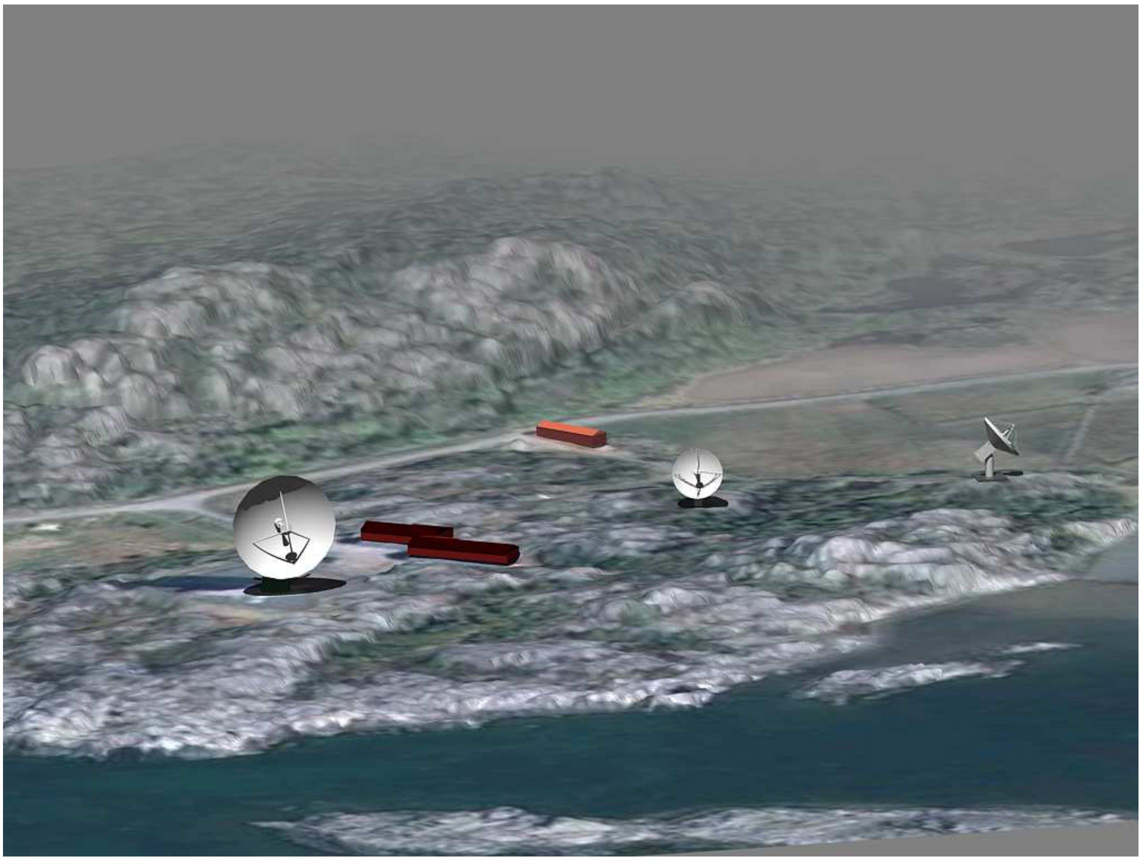

Simulations of VLBI observations with the Onsala Twin Telescope

Master of Science Thesis

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Kurzfassung

Der International VLBI Service for Geodesy and Astrometry (IVS) entwickelte das VLBI2010 Konzept um die Genauigkeit der geodätischen Very Long Baseline Interferometry (VLBI) auf 1 mm für Stationspositionen und 0.1 mm/Jahr für Stationsgeschwindigkeiten zu verbessern. Dafür sollen Breitbandbeobachtungen mit schnellen Teleskopen verwendet werden, sowie Zwillingsteleskope um die Atmosphäre besser bestimmen zu können. Diese gilt als limitierender Faktor der geodätischen VLBI. Einige Projekte zur Realisierung des VLBI Konzeptes wurden bereits gestartet, wie unter anderem das Onsala Twin Telescope Projekt, dessen Zielsetzung ist, ein Zwillingsteleskop in Onsala ab 2016 zu betreiben.

In dieser Arbeit wurde ein globales VLBI Netzwerk geplant, simuliert und analysiert. Als Grundlage wurde das CONT11 Netzwerk gewählt, eine 15 Tage lange Kampagne, die momentan die besten geodätischen Ergebnisse liefert. Die Ergebnisse des existierenden 20 m Teleskops in Onsala und des geplanten Zwillingsteleskop in Onsala wurden auf Stationspositionen, Erdorientationsparameter, Atmosphärenparameter und Uhrenschätzungen verglichen.

Eine generelle Verbesserung mit einem Zwillingsteleskop in Onsala ist erkennbar, vor allem mit einem Zwillingteleskop das kontinuierlich beobachtet und einer Strategie die 4 Quellen gleichzeitig beobachtet.

Abstract

The VLBI2010 committee of the International VLBI Service for Geodesy and Astrometry (IVS) developed a concept to achieve an improvement of the accuracy of geodetic Very Long Baseline Interferometry (VLBI) to 1 mm for station position and 0.1 mm/yr for station velocity. This so-called VLBI2010 concept includes broad-band observations with fast slewing telescopes and proposes twin telescopes to improve the handling of atmospheric turbulence that has been identified as a limiting factor for geodetic VLBI. Several international projects following the VLBI2010 concept have been started in the last years. One of them is the Onsala Twin Telescope project which is expected to start operating in 2016.

In this study a global VLBI network is scheduled, simulated and analysed. The chosen network is the CONT11 network, a 15 days long continuous VLBI campaign performed in 2011 that gave the current state-of-the-art geodetic VLBI results. Results derived from simulated observations in this network including either the legacy 20 m radio telescope at Onsala or the planned Onsala Twin Telescope are compared. The comparisons include station positions, earth orientation parameter, atmospheric parameter and clock estimations. A general improvement can be noted with the Onsala twin telescope.

The best results are derived with the twin telescope operating in continuous mode and a 4 source observed simultaneously strategy.

Sammanfattning

Den International VLBI Service for Geodesy and Astrometry (IVS) utvecklade VLBI2010 konceptet för att förbättra noggrannhet av de geodetiska Very Long Baseline Interferometry (VLBI) till 1 mm i stationsposition och 0,1 mm/år i stationshastigheter. Daför skall bredband observationer användas med snabbare teleskop och tvillingsteleskop för att förbättra hanterringen av atmosphäriska störeffekter, som är den begränsade faktor i geodetiska VLBI mätningar idag. Några projekt som följer VLBI2010 konceptet har redan börjat, be.a Onsala Twin Teleskop projektet, som skall bli operativt 2016.

I detta arbete planerades, simulerades och analyserades ett globalt VLBI nätverk, CONT11. Det är en 15 dagar lång kampanj, vilken gav de bästa geodetiska resultat någonsin. Resultaten för stationsposition, jordorienteringsparametrar, atmosfäriska parametrar och klockestimat jämfärdes för två olika strategier som ver att använda det befintliga 20 m teleskopet på Onsala eller det planerades Onsala tvillingteleskopet.

Generellt blir där en förbättring genom att anvenda tvillingteleskopet på Onsala, speciellt när det används i kontinuerlig mod.

Acknowledgments

I thank Harald Schuh, who had the connections to the Chalmers University of Technology in Gothenburg, Sweden.

A big thanks to Rüdiger Haas and Johannes Böhm who coached me during all phases in this thesis. They taught me a lot and I learned much.

Thanks to the VLBI team in Vienna, who answered all my questions I had concerning VieVS.

Another big thanks to my friends in Sweden, who made my time in Sweden really pleasant.

Thanks to my family, who is always supporting me.

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Glossary

bps bit per second

DORIS Doppler Orbitography and Radiopositioning Integrated by Satellite

EGR East gradient

EOP Earth Orientation Parameters

GEO Department of Geodesy and Geoinformation

GNSS Global Navigation Satellite System

GPS Global Positioning System

ICRF International Celestial Reference Frame

ITRF International Terrestrial Reference Frame

IVS International VLBI Service for Geodesy and Astrometry

Jy Jansky: flux unit

LEO Low Earth Orbiter

LLR Lunar Laser Ranging

mas Milliarcsecond

NGR North gradient

NGS National Geodetic Survey

NNR No Net Rotation

NNT No Net Translation

OTT Onsala Twin Telescope

ppb parts per billion

RMS Root Mean Square

SAAT source at a time

SEFD antenna system equivalent flux density

SLR Satellite Laser Ranging

SNR Signal-to-noise ratio

TRF Terrestrial Reference Frame

UT Universal Time

VieVS Vienna VLBI Software

VLBI Very Long Baseline Interferometry

ZHD Zenith Hydrostatic Delay

ZWD Zenith Wet Delay

Chapter 1

Introduction

1.1 Aim of the work

Geodetic Very Long Baseline Interferometry (VLBI) has played an important role in providing high-precision geodetic data. When the technique was developed in the 1970's, the accuracy was on the order of one meter. Nowadays, VLBI has an accuracy of about 5 mm. This accuracy should be improved to 1 mm in station position and 0.1 mm/yr in station velocity with the VLBI2010 concept, developed by the International VLBI Service for Geodesy and Astrometry (IVS). To reach this ambitious goal, the concept includes small and fast antennas, and suggests to build twin telescopes.

Previous studies proved that the number of observation is increasing with a twin telescope, but there have not been any analyses on improvements of baseline length repeatability or atmospheric parameters yet. Actually, it is a completely new era of VLBI without any experiences.

This work compares the results that can be achieved if the existing Onsala 20 m telescope will be replaced by a twin telescope following the VLBI2010 concept.

(Niell et al.; 2005)

1.2 Very Long Baseline Interferometry - VLBI

1.2.1 Principle

Geodetic VLBI is a geodetic space technique which is very important to monitor geodynamical, astronomical and physical phenomena. The principle of geodeticVLBI is shown in Figure 1.1. Radio signals emitted by natural radio sources (e.g. quasars) are received and recorded by at least 2 radio telescopes. Those radio sources send out spherical waves, but the wave fronts reaching the earth are flat, because of the huge distance. Geodetic VLBI is today observing in X-Band (8.4 GHz) and S-Band (2.3 GHz) to be able to reduce ionospheric effects. After a data correlation, the time delay of the signal between two stations can be derived. With this time delay, results of VLBI are determined.

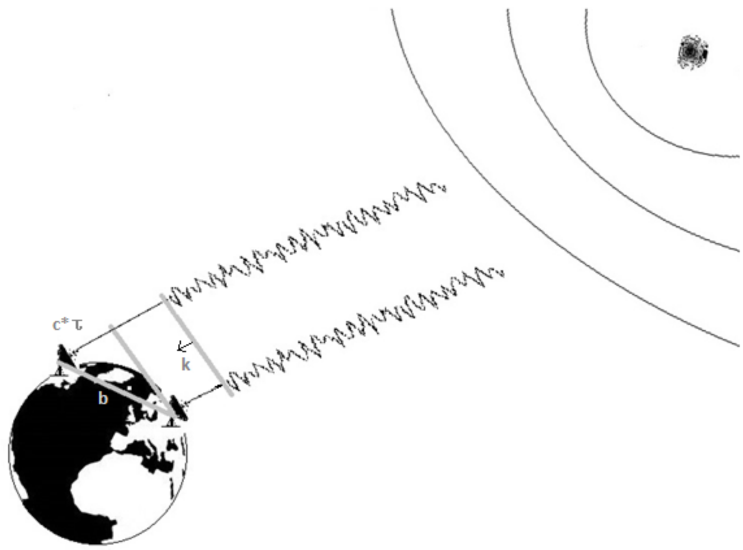

Figure 1.1: Principle of VLBI

(Sovers and Fanselow; 1998)

1.2.2 VLBI Results

As is shown in Table 1.1, geodetic VLBI is the only method to determinde UT1 - UTC and long term nutation. Furthermore VLBI observations are used to realize the CRF and to provide the complete set of Earth Orientation Parameters (EOP) (nutation [dX, dY], polar motion [xp ,yp], UT1-UTC). Baseline length and station velocities are calculated to support the realisation of the TRF with a stable scale. It is also important to link national frames with the ITRF. Moreover, VLBI is used for climate and relativistic studies.

Table 1.1: Comparison of different geodetic space techniques (modified from Rothacher)

Parameter	VLBI	GNSS	DORIS	SLR	LLR	Altimetry
ICRF	X					
Nutation	X	(X)		(X)	X	
Polar Motion	X	X	X	X	X	
UT1	X					
Length of Day	(X)	X	X	X	X	
ITRF	X	X	X	X	X	(X)
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time Freq./Clocks	X	X		(X)		
Geocenter		X	X	X		X
Gravity Field		X	X	X	(X)	X
Orbits		X	X	X	X	X
LEO Orbits		X	X	X		X

1.3 VLBI Delay Model

The simplified VLBI delay model can be formulated as:

$$-c * \tau = b * k + \Delta\tau_{clock} + \Delta\tau_{tropo} + \Delta\tau_{iono} + \Delta\tau_{rel}$$

c ... speed of light in vacuum

τ ... time delay

b ... baseline vector between two stations

k ... unit source vector in the direction of the radio source

$\Delta\tau_{clock}$ ... delay correction due to clock errors

$\Delta\tau_{tropo}$ ... neutral atmospheric delay correction

$\Delta\tau_{iono}$ ... ionospheric delay correction

$\Delta\tau_{rel}$ ... delay correction due to relativistic effects

(Teke et al.; 2012)

1.4 Atmospheric delays

Radio source signals recorded on the Earth have to pass the Earth's atmosphere. Therefore it is important to know about the atmosphere's structure and behaviour. The atmosphere is regarded as the limiting factor for geodetic VLBI observations. Atmospheric effects on signals can be divided into two parts: Path delay in the neutral atmosphere and in the electrically charged atmosphere.

1.4.1 Path delay in the electrically charged atmosphere

The electrically charged atmosphere is the part of the atmosphere above 60 km, where the propagation velocity of VLBI signals is dependent on its frequency. This results in a different phase and group velocity.

Ionospheric group delays are calculated with:

$$\Delta\rho_{gr}^{ion}[m] = \frac{40.31}{f^2}\int N_e ds_0$$

f ... frequency

N_e ... ionospheric electron density

s_0 ... ray path

The ionospheric delay is reduced from the observed delay in the further analysis.

(Rizos; 1999)

1.4.2 Path delay in the neutral atmosphere

The neutral atmosphere is the part of the atmosphere up to 100 km. It includes the troposphere, stratosphere and mesosphere, but usually the term tropospheric delays is used for the delay in the neutral atmosphere. For geodetic VLBI observations, the neutral atmosphere is not frequency dependent. This means that the phase and the group delays are the same. A signal takes the fastest electrical path through a medium, which is not the geometrically shortest way, as shown in Figure 1.2.

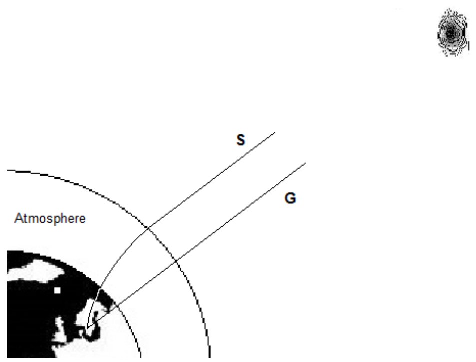

Figure 1.2: Path delay in the neutral atmosphere. The path G is the geometrical shortest way through a medium, but a signal takes the path S, which is the fastest electrical path.

The tropospheric path delay ΔL is calculated as

$$\Delta L = \int n(s)ds - G$$

It can be divided into an hydrostatic delay ΔL_h and a wet delay ΔL_w.

$$\Delta L = \Delta L_h + \Delta L_w + S - G$$

Atmospheric delays are calculated in zenith direction. A mapping function is used to map the zenith delay to the elevation angle of the observation.

- Zenith Hydrostatic Delay (ZHD)

  The ZHD can be derived from the total pressure at a station with the equation of Saastamoinen (1972):

$$\Delta L_h^z[m] = 0.0022768 * \frac{p_0[hPa]}{f(\phi, h_{ref})}$$

p ... Pressure at a station

ϕ ... Latitude

h_{ref} ... ellipsoid height

- Zenith Wet Delay (ZWD)

  There is no easy equation for the ZWD as there is for the ZHD. This is due to the large temporal and spatial variations of water vapour in the atmosphere. Normally, zenith wet delays are estimated in VLBI or GPS analysis. It varies between 0 mm at the poles and 400 mm close to the equator.

1.4.3 Mapping functions

The zenith wet delay is mapped with a mapping function to the elevation angle e of the observation.

$$\Delta L(e) = \Delta L^z * mf(e)$$

There is a separation in mapping functions in a wet and a hydrostatic mapping function. The wet mapping function (Böhm et al.; 2006) is always larger than the hydrostatic one, except for very low elevation angles, because the bending effect is added to the hydrostatic mapping function.

For a flat and stratified atmosphere the mapping function is $1/sin(e)$.

Different mapping functions were developed in the past. At a current status, the best is the Vienna Mapping function, which is based on ray-tracing through actual meteorological data.

A wrong mapping function mf' results in a wrong station height as shown in Figure 1.3.

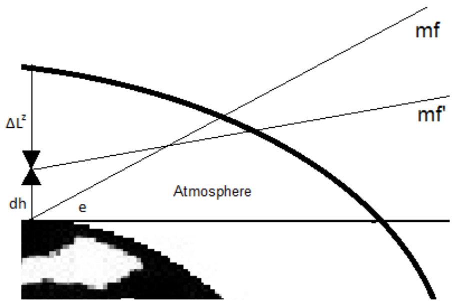

Figure 1.3: Effects of a wrong mapping function on station height

(Böhm; 2011)

1.5 VLBI2010

From 2003 to 2005 the IVS Working Group 3 defined goals and requirements for future VLBI observations to improve accuracy of VLBI results and developed certain strategies and recommendations. The main goal is a position accuracy of 1 mm and a velocity accuracy of 0.1 mm/yr on global scales. This should be realised with a better geographical antenna distribution, reduction of errors, more observations and new observation strategies. In Table 1.2 the design aspects of VLBI2010 are shown to realize those goals. Smaller but faster antennas, a broader frequency range with a higher recording rate and a lower antenna sensitivity, often expressed as SEFD are the main improvements. Also the transfer of data to correlators should be faster. There are already VLBI2010 telescopes in Australia and the first twin telescope was built in Wettzell, Germany. Several telescope projects are already accepted e.g in Spain, Portugal, Russia and Japan.

(Petrachenko et al.; 2009)

Table 1.2: VLBI2010 goals ((Petrachenko et al.; 2009))

	Current	VLBI2010
antenna size	5 - 100 m	12 m
slew speed	20 - 200 °/min	$\geq$ 360 °/min
SEFD	200 - 15.000	$\leq$ 2.500
frequency range	S/X band	2 - 14 (18) GHz
recording rate	128 - 512 Mbps	8-16 Gbps
data transfer	usually ship disks, some e-transfer	e-transfer, e-VLBI, ship disks when required

1.6 Onsala Space Observatory

The Onsala Space Observatory is operated by the Department of Earth and Space Sciences at the Chalmers University of Technology. It is located 45 kilometres south of Gothenburg. For VLBI the Onsala Space Observatory is currently equipped with two telescopes of 25 m and 20 m diameter.

- The 25 m telescope was built in 1963 and is operating since 1968 in VLBI experiments. It is the first European radio telescope to be used in VLBI. Nowadays, it is observing at wavelengths of 4-40 cm and is mainly used for astronomical VLBI.

- The 20 m telescope was built in 1976. It is surrounded by a radome to be protected against wind, snow and rain. The observed wavelengths are between 3 mm and some cm. Due to its location in the north and the equipment the 20 m telescope is a very important part in VLBI observations.

An overview of the Onsala Space Observatory is shown in Figure 1.4.

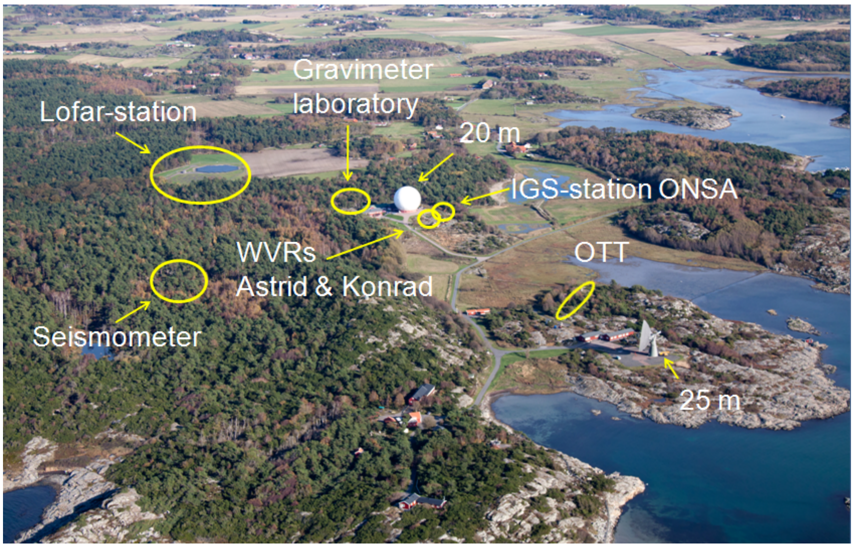

Figure 1.4: Overview of the Onsala Space Observatory

(OSO; 2013)

1.7 The Onsala Twin Telescope

The Onsala Twin Telescope (OTT) was proposed 2011. The project was accepted in 2012 by the 'Knut and Alice Wallenberg Foundation'. The expectation is that the Onsala twin telescope will operate regulary in 2016.

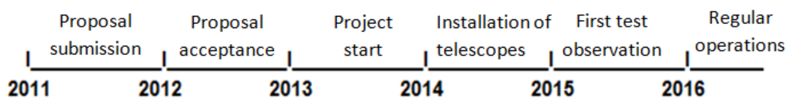

Figure 1.5: Timeline of the twin telescope at Onsala

1.7.1 Position

Figure 1.6 shows the planned location of the twin telescope. It was chosen with respect to ground height difference, closeness to the sea and the natural reserve.

Figure 1.6: Planned location of the twin telescope at Onsala

1.7.2 Observing modes for a twin telescope

- Multidirectional mode:

  The two antennas are part of different subnets at the same time by observing separately different sources in different directions. This leads to more observations and a strengthened geometry. Additional, different subnets at the same time are tied.

- Continuous mode:

  One of the two antennas is always observing. While the observation the other antenna is slewing to the next radio source. This leads to a continuous observation without any temporal gaps.

- Maintenance mode:

  There is also the possibility that one antenna is observing, while the other one is not available, e.g. because of maintenance.

(Sun et al.; 2012)

Figure 1.7: The Twin telescope in Wettzell, Germany (http://www.tum.de/die-tum/aktuelles/pressemitteilungen/kurz/article/30823/)

1.8 CONT campaigns

The CONT campaigns demonstrate the highest accuracy of the currently existing geodetic VLBI system. This campaign allows an analysis of EOP variations,in particular the verification of ocean tide models and tests of theoretical models and also supplies data for atmospheric research to improve weather models. CONT campaigns are performed every three years since 2002 and started in 1994.

The CONT11 campaign was observed between Thursday, September 15, 2011 at 00:00:00 UT and Thursday, September 29, 2011 at 23:59:59 UT. It involved a network of stations as shown in Figure 1.8. The station WARK12M in New Zealand had to cancel its participation because of technical problems. Thirteen stations, geographically balanced (9 stations on the northern hemisphere and 4 stations on the southern hemisphere) took part in this 15 days campaign. Table 1.3 shows detailed information for each station.

Figure 1.8: Participating stations in the CONT11 campain (http://ivscc.gsfc.nasa.gov/program/cont11/cont11.jpg)

(IVS; 2012)

Table 1.3: Stations participating in the CONT11 campaign

Station	Code	Diameter [m]	Slew rate Az [°/min]	Slew rate El [°/min]	Longitude [°]	Latitude [°]	Country
BADARY	Bd	32	72	48	257.76	51.77	Russia
FORTLEZA	Ft	14.2	40	20	38.43	-3.88	Brazil
HARTRAO	Hh	26	240	120	332.31	-25.89	South Africa
HOBART12	Hb	12	300	75	212.56	-42.80	Australia
KOKEE	Kk	20	117	117	159.67	22.13	USA
NYALES20	Ny	20	120	120	348.13	78.93	Norway
ONSALA60	On	20	144	60	348.07	57.40	Sweden
TIGOCONC	Tc	6	360	180	73.04	-36.82	Chile
TSUKUB32	Ts	32	180	180	219.91	36.11	Japan
WESTFORD	Wf	18	200	120	71.49	42.61	USA
WETTZELL	Wz	20	180	90	347.12	49.15	Germany
YEBES40M	Ys	40	60	60	3.09	40.52	Spain
ZELENCHK	Zc	32	72	48	318.43	43.79	Russia

1.9 Scheduling

A schedule is a complete observation plan for a VLBI session. Necessary a priory information that is stored in catalogue files includes:

- Station dependent information:

  position (X, Y, Z, longitude, latitude, ellipsoidal height), antenna parameters (diameter, slew velocity), electronics and recorders,..

- Source dependent information:

  positions (declination, right ascension), flux models.

Furthermore every schedule has to be adjusted to the aim of a session, which results in a complete list of all scans.

(Gipson; 2010)

1.9.1 Scheduling programs

- SKED:

  The basic program was developed by Nancy Vandenberg in 1978. That time scans were selected manually. In 1990, the automatic scheduling was introduced. It was continuously improved to an automatic scheduling program with features like the fill in mode. This program is used for geodetic VLBI as well as for astronomic VLBI. (Gipson; 2010)

- vie_sched:

  This program was developed by Jing Sun in 2010 and is written in MATLAB. It considers all VLBI2010 requirements with a more uniform network and fast moving antennas. Therefore vie_sched invented a source-based scheduling next to the common station-based scheduling. Furthermore, it is possible to schedule multiple antennas at one site. (Sun; 2013)

1.9.2 Strategies of scheduling

There are at least two different strategies to schedule observations.

- Station based strategy:

  This strategy aims at a good local sky coverage, which is important for ZWD estimations, clock parameters and station height. It is realised in NASA SKED and vie_sched.

- Source based strategy:

  In this strategy, originally proposed by Bill Petrachenko and Anthony Searle, the scheduling program selects 2 or 4 sources with no respect to their effects on individual stations, as shown in Figure 1.9. Subnets are formed and all stations in one subnet observe the same source. It is designed for a global station distribution with fast moving antennas. A good global sky coverage and good number of observation will be achieved. It is realised in vie_sched and used for this thesis, because it is at a current status the only program to schedule twin telescope.

  (Sun; 2013)

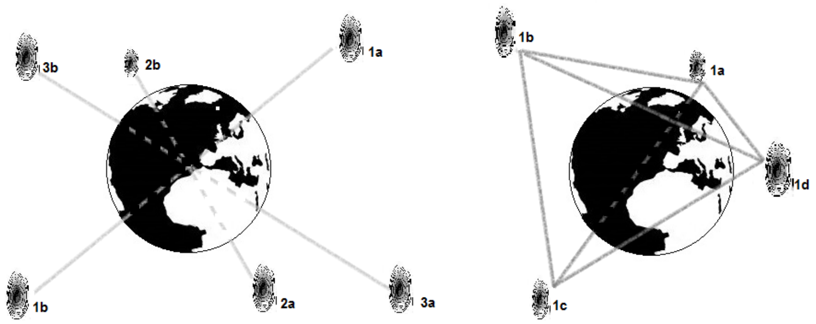

Figure 1.9: Possible source distribution of 2 or 4 sources observed simultaneously strategy. left: 2-SAAT in 3 different scans; right: 4-SAAT

- Fill in mode: Additional to those strategies a fill in mode is available. In networks with different telescopes at each site, bigger telescopes have idle times. To reduce this gaps, subnets with those telescopes are created to observe other sources.

(Gipson; 2010)

1.9.3 CONT11 schedule

The schedule for the CONT11 campaign was created with the NASA sked program with respect to scheduling parameters like: minimum Signal-to-noise ratio (SNR) levels, source list and flux models but also with compromises in optimum simulated formal errors, number of observations, number of scans per hour and sky coverage.

(IVS; 2012)

1.10 Vienna VLBI Software - VieVS

At the Department of Geodesy and Geoinformation (GEO) at the Vienna University of Technology, an associate IVS Analysis Center, this software has been developed since 2008 to fulfill present requirements of VLBI2010. In March 2013 Version 2.1 was released. VieVS is written in Matlab. Therefore it is easy and fast to edit the source code, if necessary. It is used to analyse data and estimate parameters (e.g. troposphere, clock or station coordinates). Every task is realised in an own module, as shown in Figure 1.10. For this thesis the coloured modules were used and they are described in the next step.

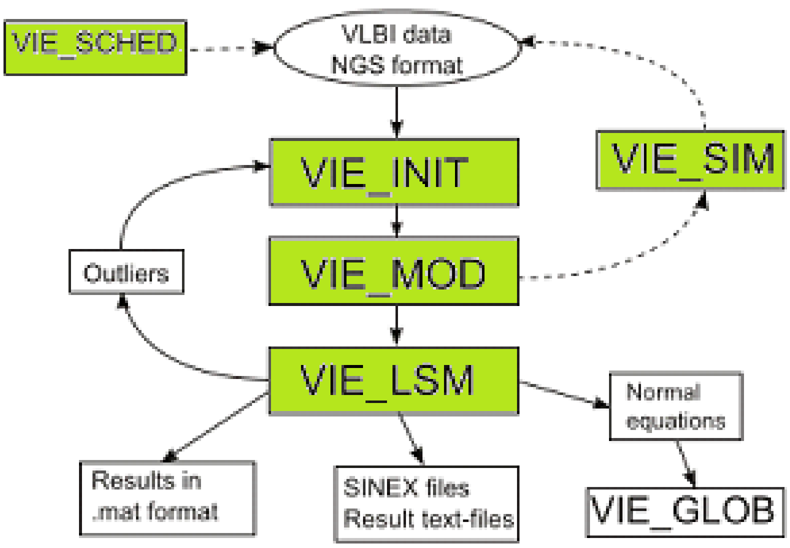

Figure 1.10: Modules of VieVS (Nilsson et al.; 2011)

- vie_sched

  This module was developed by Jing Sun with the purpose of a 'Next Generation Scheduling for VLBI2010'. It provides next to the existing station based strategy a source based strategy, which is faster and advantageous. For twin telescopes two different observing modes are available. (Sun; 2013)

- vie_init

  VLBI data in NGS format is read in.

- vie_mod

  In vie_mod, theoretical delays and their derivatives are calculated related to unknown parameter (e.g. station coordinates or earth orientation).

- vie_sim

  The vie_sim module can add to a theoretical delay, calculated in vie_mod, a wet troposphere (using the method by Nilsson and Haas (2010)), clocks (random walk simulation) and observation noise (white noise). It uses

- vie_lsm

  Vie_lsm estimates unknown parameters: station clocks, zenith tropospheric delays, horizontal tropospheric gradients, Earth orientation parameters, station coordinates, and the coordinates of selected radio sources by using the least-squares method.

(Nilsson et al.; 2011)

1.11 Sources

Suitable radio sources for geodetic VLBI need good characteristics in positional stability, flux density, source structure indices and distribution on the sky. They are categorized for X and S band separately. (Sun; 2013)

1.11.1 Source catalogues

Two different source catalogues were provided for this thesis. Their position distribution is shown in Figure 1.11 and Figure 1.12. The different colours indicate their flux values for S-Band observations.

- CONT11 source catalogue

  This catalogue includes the 117 sources, that were used for the original CONT11 schedule.

- VieVS source catalogue

  Jing Sun analysed radio sources for geodetic observations in her PhD thesis. 211 suitable sources were provided and called the VieVS source catalogue in this thesis.

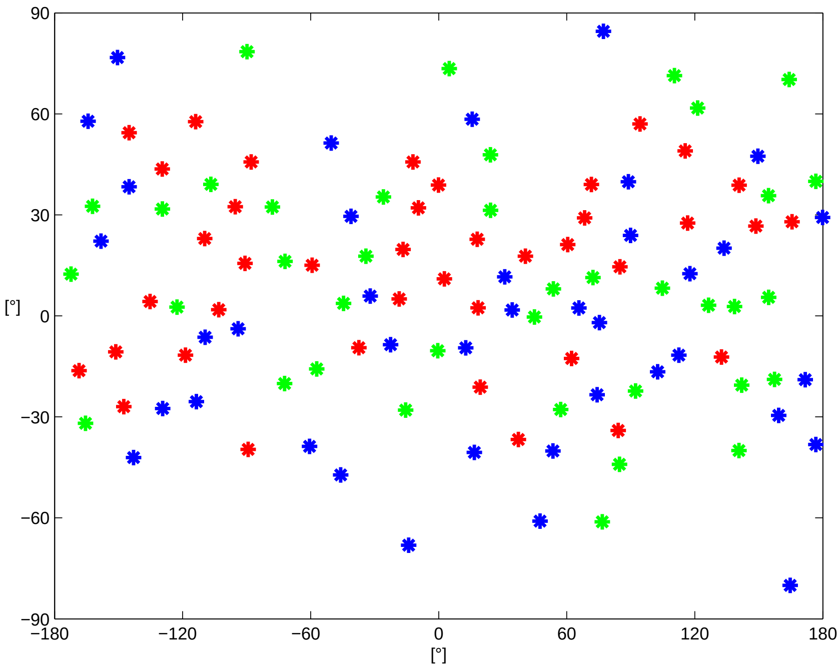

Figure 1.11: CONT11 source catalog; blue: flux $\geq$ 0.5 Jy; green: 0.25 $<$ flux $\geq$ 0.25 Jy; red: flux $<$ 0.25 Jy

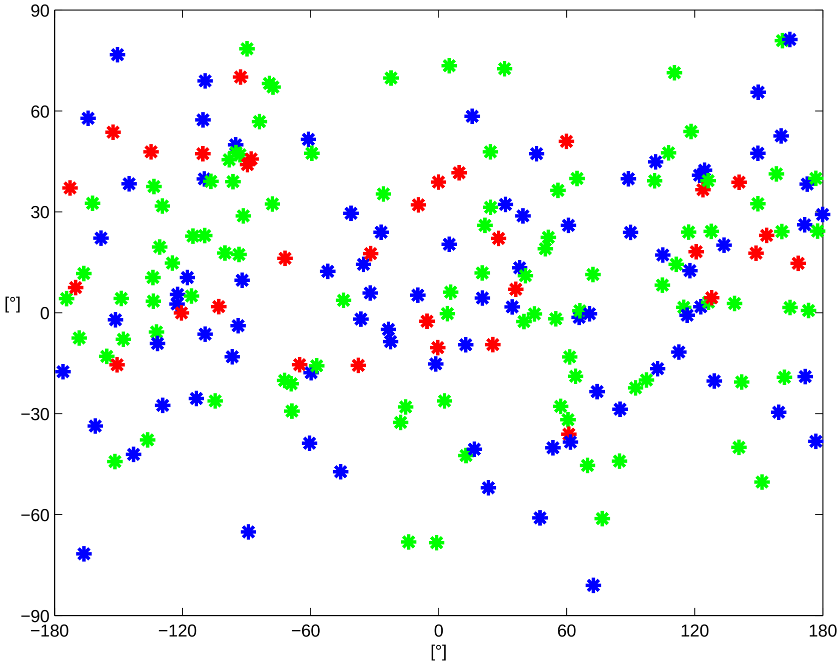

Figure 1.12: VieVS source catalog; blue: flux $\geq$ 0.5 Jy; green:0.25 $<$ flux $\geq$ 0.25 Jy; red: flux $<$ 0.25 Jy

The VieVS source catalogue contains more sources and especially more strong sources as shown in Figure 1.13. Furthermore there are more sources in polar regions as shown in Figure 1.14.

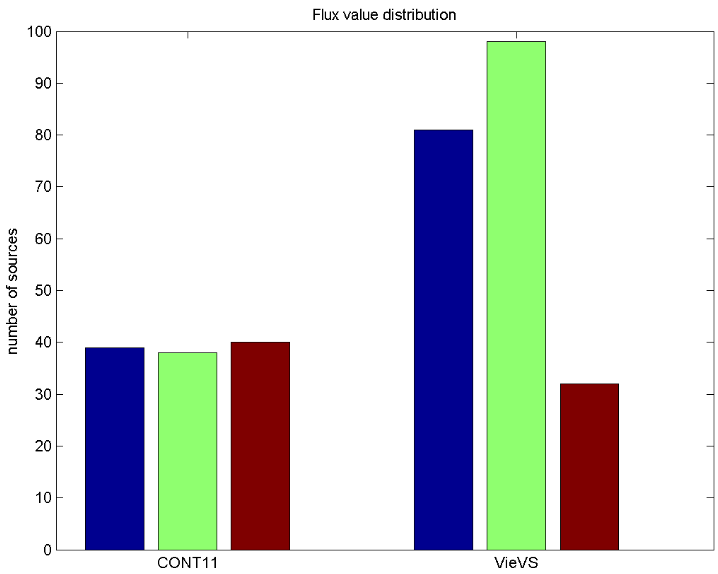

Figure 1.13: Flux value distribution of source catalogues. blue: flux $\geq$ 0.5 Jy; green:0.25 $<$ flux $\geq$ 0.25 Jy; red: flux $<$ 0.25 Jy

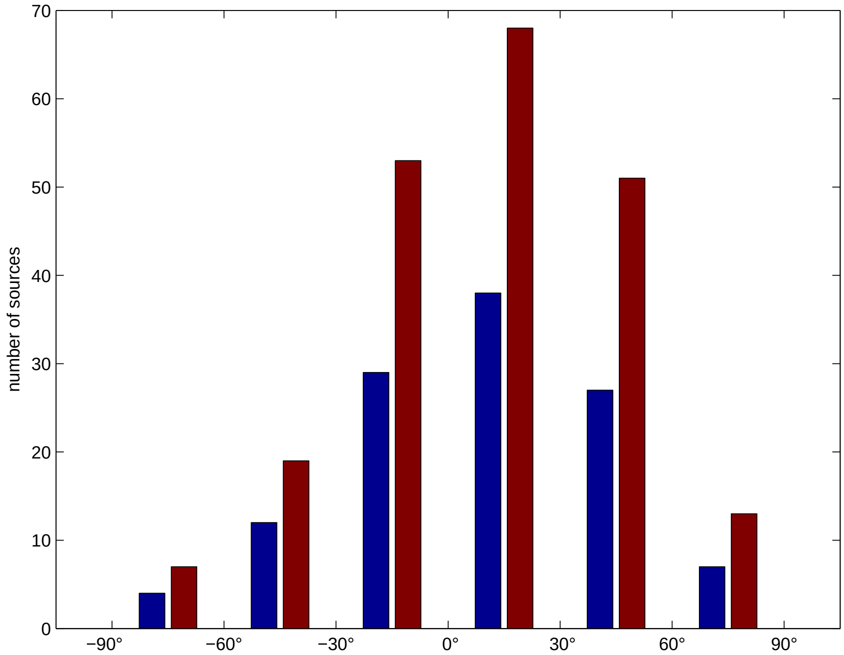

Figure 1.14: Geographical distribution of source catalogues. blue: CONT11 source catalogue; red: VieVS source catalogue;

Chapter 2

Experiments

The basis campain for this thesis is the CONT11 campain. It demonstrates the highest accuracy of the current VLBI system with a 15 days continuous observation from Thursday September 15, 2011 at 00:00:00 UT to Thursday September 29, 2011 at 23:59:59 UT. Fourteen stations were participating as it is shown in Figure 1.8, but WARK12M in New Zealand had to cancel its participation because of technical problems.

This campaign allows an analysis of EOP variations,in particular the verification of ocean tide models and tests of theoretical models and also supplies data for atmospheric research to improve weather models. (IVS; 2012)

2.1 Estimated Parameters

Estimation of parameters are done with vie_lsm in a least squares adjustment.

- Clock offset: one quadratic term; every 60 minutes; in cm; relative constraints of 0.5 ps^2/s
- ZWD: every 30 minutes; in cm; relative constraints of 0.7 ps^2/s
- NGR: every 6 hours; in cm; relative constraints of $2mm/day$
- EGR: every 6 hours; in cm; relative constraints of 2 mm/day
- EOP: in mas or ms; strong relative constraints of 1.0e-4 $(mas/ms)/day$ results to once per day

- Station coordinates: once per day; in cm; using NNT/NNR condition

2.2 Adaptation of turbulence values

The observed data of the CONT 11 session was compared with a 100 days vie_sim simulation of the first day in baseline length repeatability. The result is shown in Figure 2.1. In this simulation atmospheric parameters derived from GPS data (provided by Tobias Nilsson) were used. They are shown in Table 2.1.

Table 2.1: Turbulence parameter for every site participating in the CONT11 session

Site Name	Cn [10^{-7} $m^{-1/3}$]
BADARY	1.37
FORTLEZA	2.46
HARTRAO	1.34
HOBART12	1.60
KOKEE	1.39
NYALES20	0.65
ONSALA60	2.19
TIGOCONC	2.08
TSUKUB32	3.45
WESTFORD	2.30
WETTZELL	1.50
YEBES40M	1.48
ZELENCHK	1.86

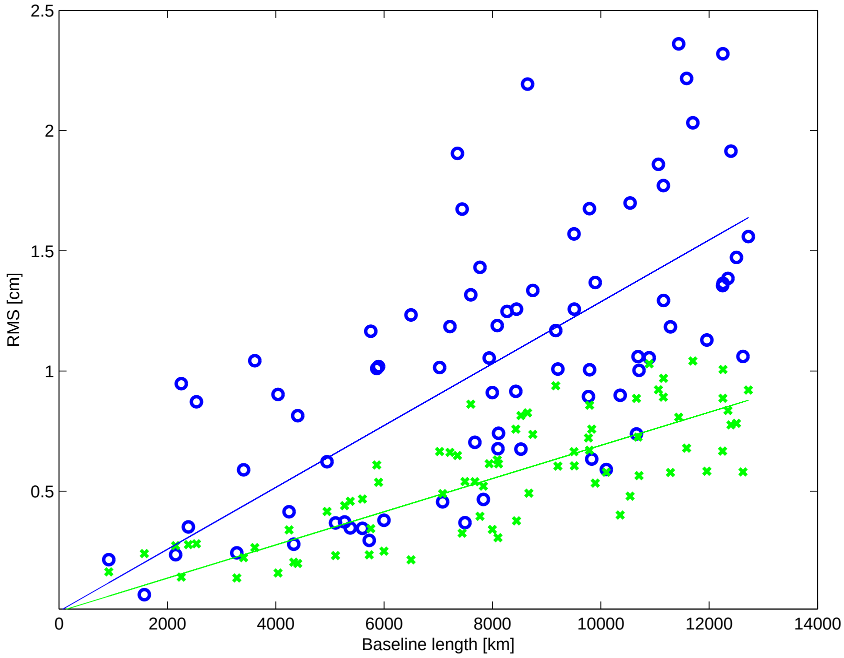

Figure 2.1: Baseline length repeatability of the original CONT11 data and a simulation of the first day. blue: original CONT11 data; green: simulation

It is shown that the simulation is about 1 ppb better than the observed data. This leads to the conclusion, that the atmospheric turbulence values are too low. After scaling the atmospheric turbulence values at each site with a scaling factor of 1.35, the baseline length repeatability are more equal, as shown in Figure 2.2. This scaling factor is used for all following experiments.

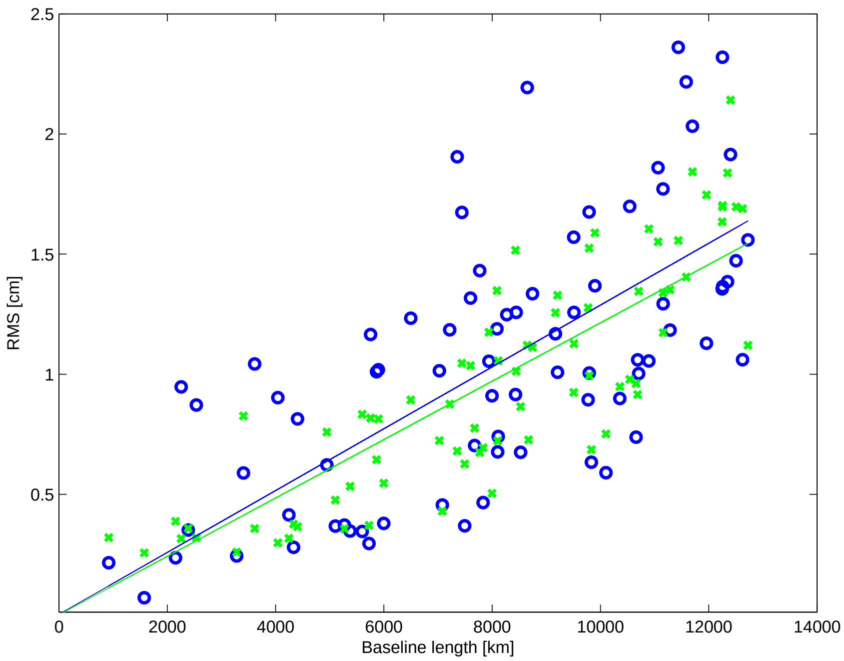

Figure 2.2: Baseline length repeatability of the original CONT11 data and a simulation with atmospheric turbulence values scaled with a factor of 1.35. blue: original CONT11 data; green: simulation

2.3 Selection of suitable schedules

To create schedules the VieVS vie_sched program was used. There are many parameters to adjust in creating a schedule, but all the further schedules are done with a

- source-based strategy
- fill in mode
- cut off elevation of 5°

The parameters source catalogue (VieVS/CONT11), flux value (0.25 Jy/0.5 Jy) and number of sources observed simultaneously (2-SAAT /4-SAAT) needed a closer look to find the best schedule for the ONSALA60 telescope and the OTT in different observing modes.

2.3.1 Schedules for the ONSALA60 telescope

A new schedule for the CONT11 campaign was done to create a basis for comparisons with the OTT.

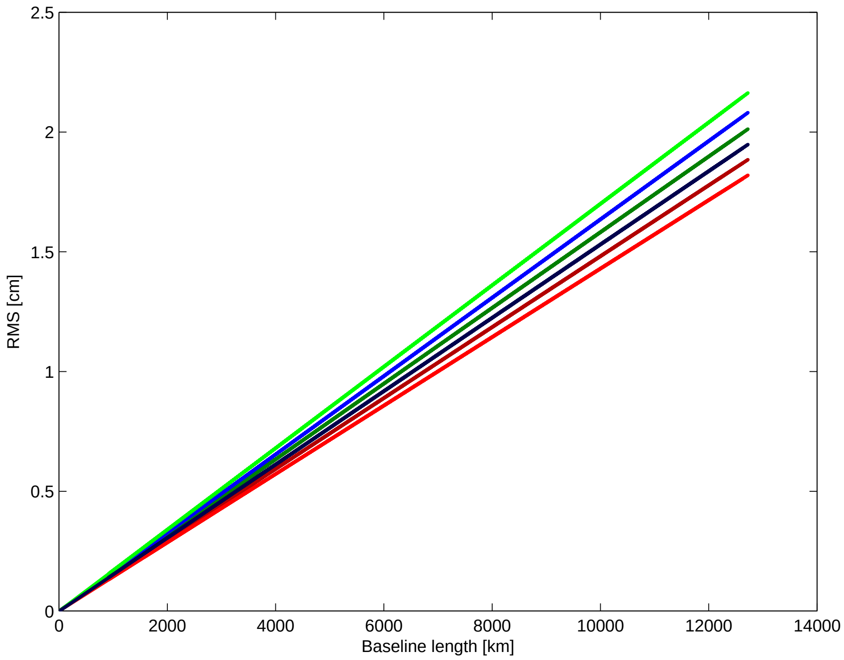

Figure 2.3: Baseline length repeatability for schedules with the ONSALA60 telescope. red: VieVS catalogue, flux $\geq$ 0.5 Jy; blue: CONT11 catalogue, flux $\geq$ 0.5 Jy; green: VieVS catalogue, flux $\geq$ 0.25 Jy; darker: 4-SAAT; brighter: 2-SAAT;

Figure 2.3 shows that the best baseline repeatability could be derived with the following options:

- VieVS source catalogue
- observing sources with a flux higher than 0.5 Jy
- source based strategy with 4 sources observed simultaneously (4-SAAT)

2.3.2 Schedules for the Onsala Twin Telescope

The existing ONSALA60 telescope was replaced by the OTT observing either in a multi-directional observing mode or a continuous observing mode. To operate a twin telescope in the multidirectional observing mode in a useful way a 4-SAAT has to be chosen. Otherwise there is only one source observable and the advantages of a twin telescope are not applicable.

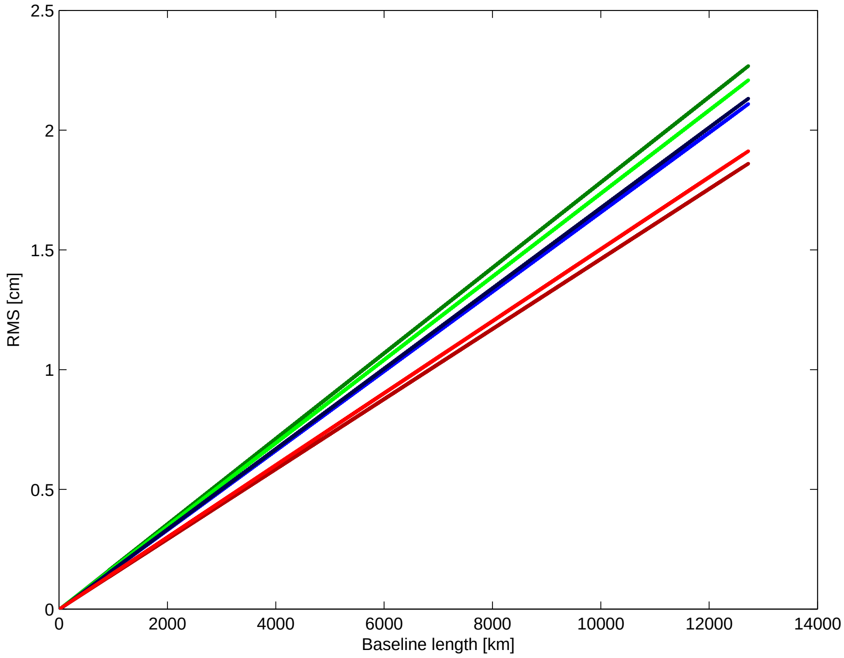

Figure 2.4: Baseline length repeatability for schedules with the OTT in a multidirectional observing mode. red: VieVS catalogue, flux $\geq$ 0.5 Jy; blue: CONT11 catalogue, flux $\geq$ 0.5 Jy; green: VieVS catalogue, flux $\geq$ 0.25 Jy; darker: 4-SAAT; brighter: 2-SAAT

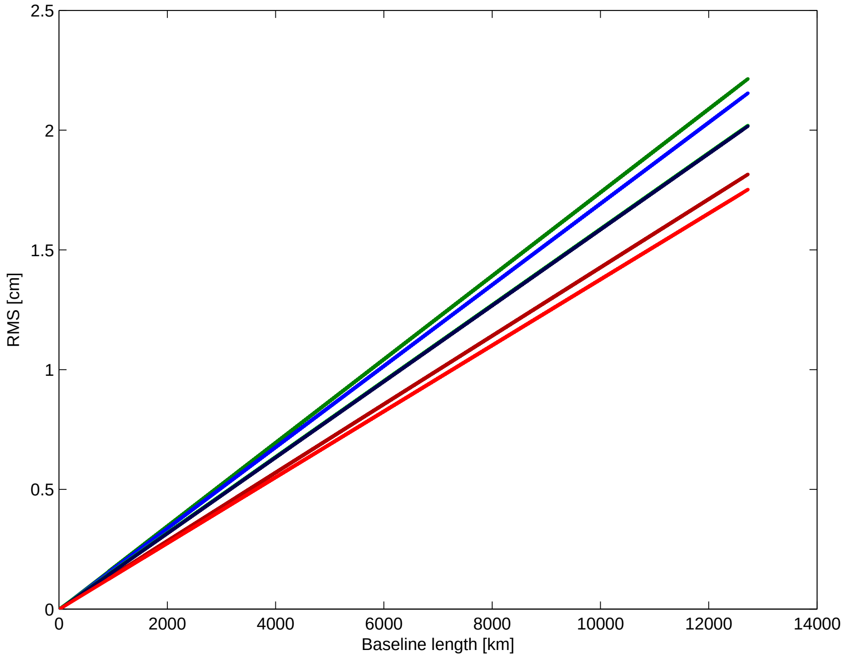

Figure 2.5: Baseline length repeatability for schedules with the OTT in a continuous observing mode. red: VieVS catalogue, flux $\geq$ 0.5 Jy; blue: CONT11 catalogue, flux $\geq$ 0.5 Jy; green: VieVS catalogue, flux $\geq$ 0.25 Jy; darker: 4-SAAT; brighter: 2-SAAT

The conclusions drawn for the ONSALA60 telescope are confirmed in Figure 2.4 and Figure 2.5 for the OTT even clearer. Schedules with the options:

- VieVS source catalogue
- observing sources with a flux higher than 0.5 Jy

are the best, but there is a controversity between the two observing modes in the number of sources. The results for the OTT in continuous, 4-SAAT mode is better than the results for the OTT in continuous, 2-SAAT mode. In the multidirectional mode it is the other way around, where 2-SAAT leads to better results than the 4-SAAT;.

2.3.3 Selected schedules

To select schedules for further analysis a threshold of 2 cm / 12000 km baseline length repeatability is chosen. Six schedules achieved this aim, shown in Figure 2.6, with a zoom in Figure 2.7.

- VieVS catalogue, flux $\geq$ 0.5 Jy, 2-SAAT
  - ONSALA60
  - OTT operating in multidirectional mode
  - OTT operating in continuous mode
- VieVS catalogue, flux $\geq$ 0.5 Jy, 4-SAAT
  - ONSALA60
  - OTT operating in multidirectional mode
  - OTT operating in continuous mode

All selected schedules used sources with a flux higher than 0.5 Jy and the VieVS source catalogue. The flux value is mainly important for small telescopes, which need a longer observing time to gain a needed SNR. In schedules that use sources with a flux value down to 0.25 Jy occur periods without an observation for smaller telescopes.

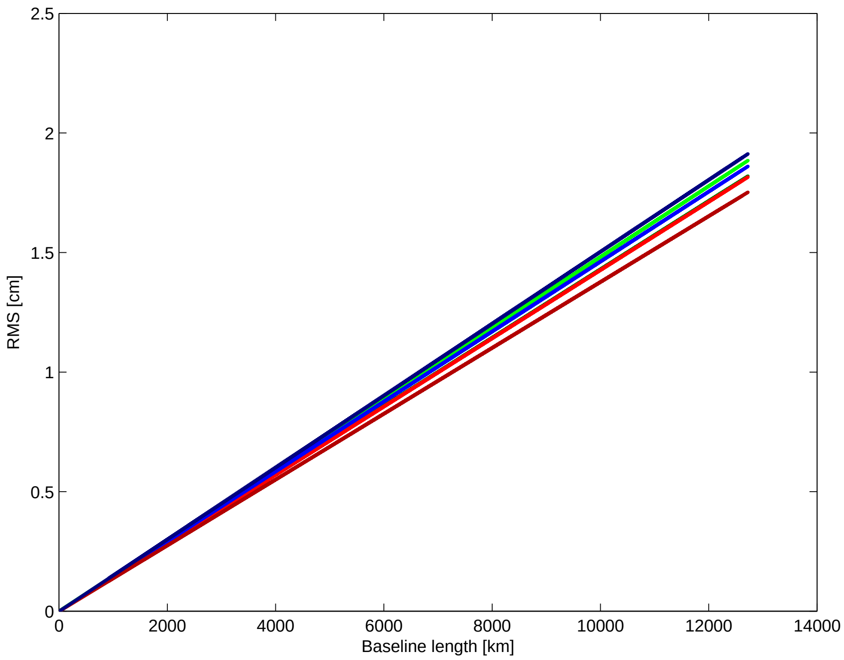

Figure 2.6: Baseline length repeatability of selected schedules. green: Onsala60 telescope; red: OTT operating in continuous mode; blue: OTT operating in multidirectional mode; darker: 4-SAAT; brighter: 2-SAAT

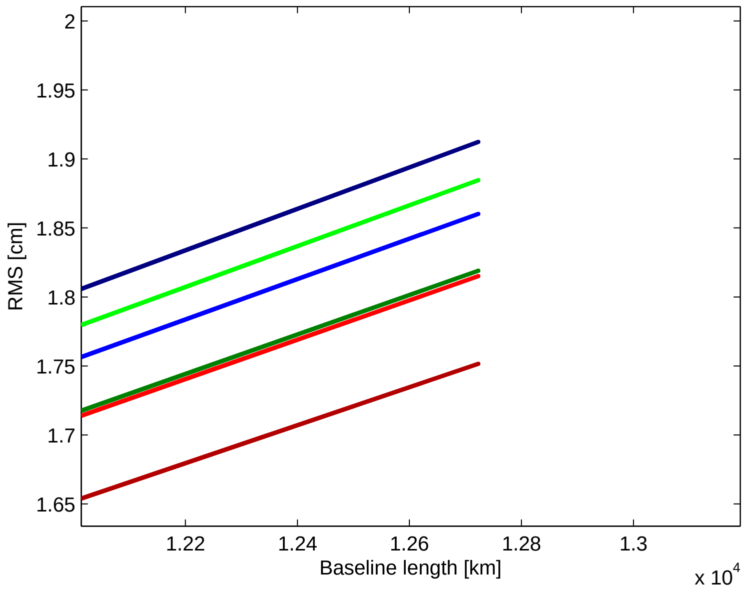

Figure 2.7: Zoom in on baseline length repeatability of selected schedules. green: Onsala60 telescope; red: OTT operating in continuous mode; blue: OTT operating in multidirectional mode; darker: 4-SAAT; brighter: 2-SAAT

Chapter 3

Results

This chapter present analyses and results with the schedules chosen in Chapter 2, where a threshold of 2 cm / 12000 km for baseline length repeatability was used. The following six schedules achieved this aim:

- VieVS catalogue, flux ≥ 0.5 Jy, 2-SAAT
  - ONSALA60
  - OTT operating in multidirectional mode
  - OTT operating in continuous mode
- VieVS catalogue, flux ≥ 0.5 Jy, 4-SAAT
  - ONSALA60
  - OTT operating in multidirectional mode
  - OTT operating in continuous mode

3.1 Baseline length repeatability

The schedules that perform best in terms of baseline length repeatability are those with the OTT in continuous mode, shown in red in Figure 2.6. In that case, 4-SAAT are better than 2-SAAT. The ONSALA60 telescope in 4-SAAT mode is nearly as good as the OTT in continuous, 2-SAAT mode. 4-SAAT are better than 2-SAAT for schedules with the ONSALA60 telescope and the OTT in continuous mode, but not with the OTT in multidirectional mode.

In general, the difference of baseline length repeatability between these 6 schedules is less than 0.2 ppb.

3.2 Baseline length repeatability for baselines with Onsala

Figure 3.1 shows the baseline length repeatability for all baselines with Onsala (ONSALA60 or OTT) for the six schedules. The OTT in continuous 4-SAAT mode give the best results.

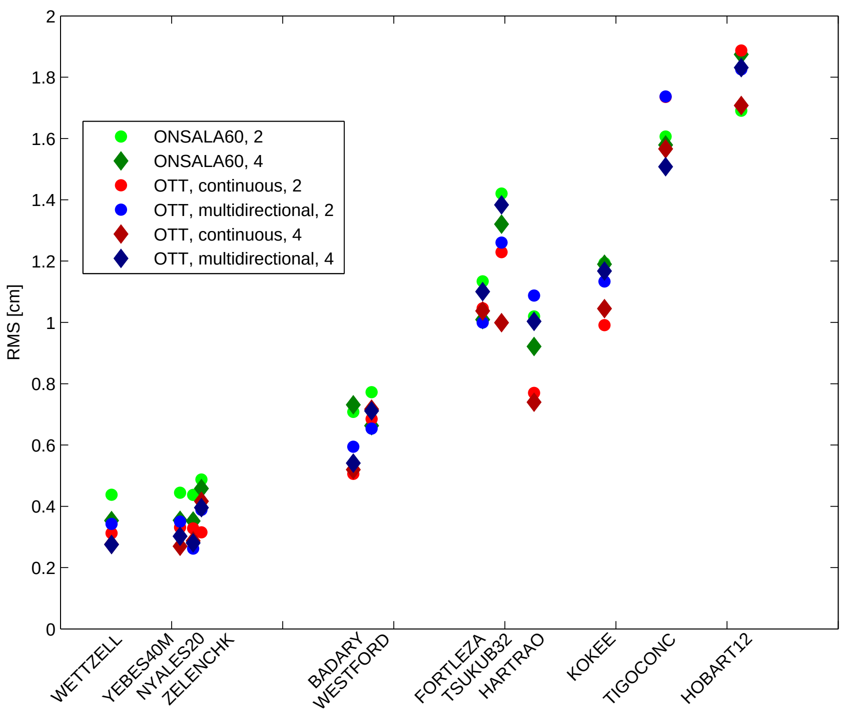

Figure 3.1: Baseline length repeatability for baselines with Onsala

3.3 Number of observations

The number of observations is a very important indicator for good VLBI results. It declares how many baselines are formed during a session. A comparison of the six chosen schedules is given in Figure 3.2.

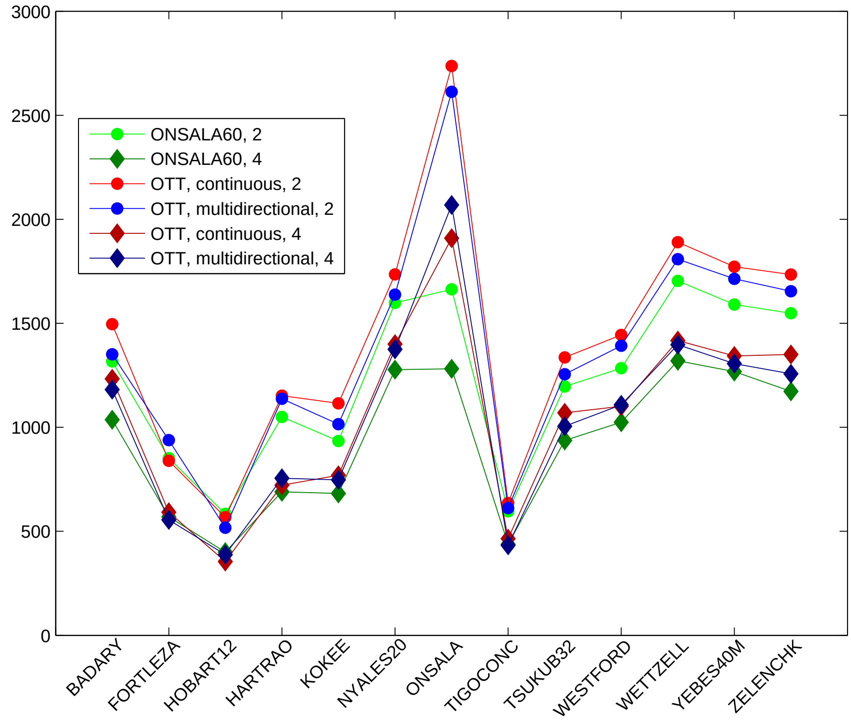

Figure 3.2: Number of observations

In general, schedules with 2-SAAT gain around 500 more observations per day than with 4-SAAT. The reason for that is the size of subnets. With 4-SAAT, subnets are smaller and less baselines are formed. The only exception is Onsala, where all schedules with the OTT gain more observations than with the existing ONSALA60 telescope. In Onsala an increase of more than 1000 observations per day are gained with the OTT compared to the ONSALA60 telescope with the same number of sources observed simultaneously. Another interesting fact is that there are more observations with a OTT in continuous mode than in the multidirectional mode.

3.4 Observation time

The observation time of each telescope is shown in Table 3.1 expressed in %. The rest of the time the telescope was idling, slewing or calibrating. It can be seen, that the observation time of a OTT is more than twice as high as the ONSALA60 telescope.

The OTT in a continuous 2-SAAT mode gain the highest observation time and the most observations as seen in 3.2.

Schedule	ONSALA60	Twin 1	Twin2
ONSALA60, 2	44		
ONSALA60, 4	44		
Twin, continuous, 2		47	50
Twin, continuous, 4		43	47
Twin, multidirectional, 2		46	49
Twin, multidirectional, 4		46	44

Table 3.1: Observation Time in %

3.5 Number of scans

Next to the number of observations the number of scans per station changes. It expresses the number of observed sources. A comparison of the 6 chosen schedules is given in Figure 3.3.

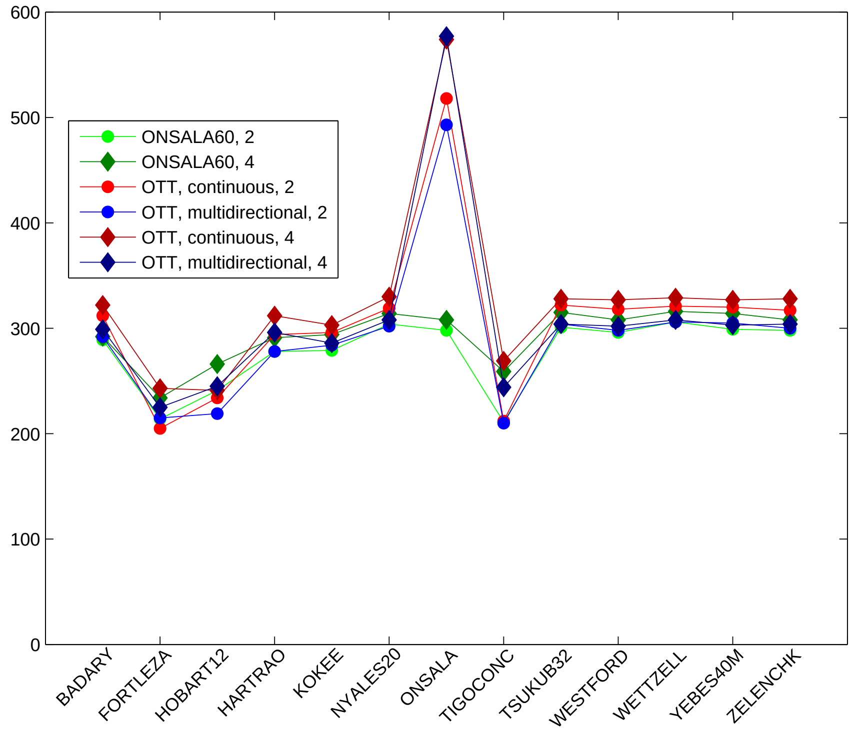

Figure 3.3: Number of scans

Schedules with 4-SAAT gain more scans, than comparable schedules with 2-SAAT. Smaller subnets are formed and slower telescopes delay other stations less. For 11 of 13 stations the OTT in continuous, 4-SAAT mode gives most scans at each station.

3.6 Estimation of zenith wet delays

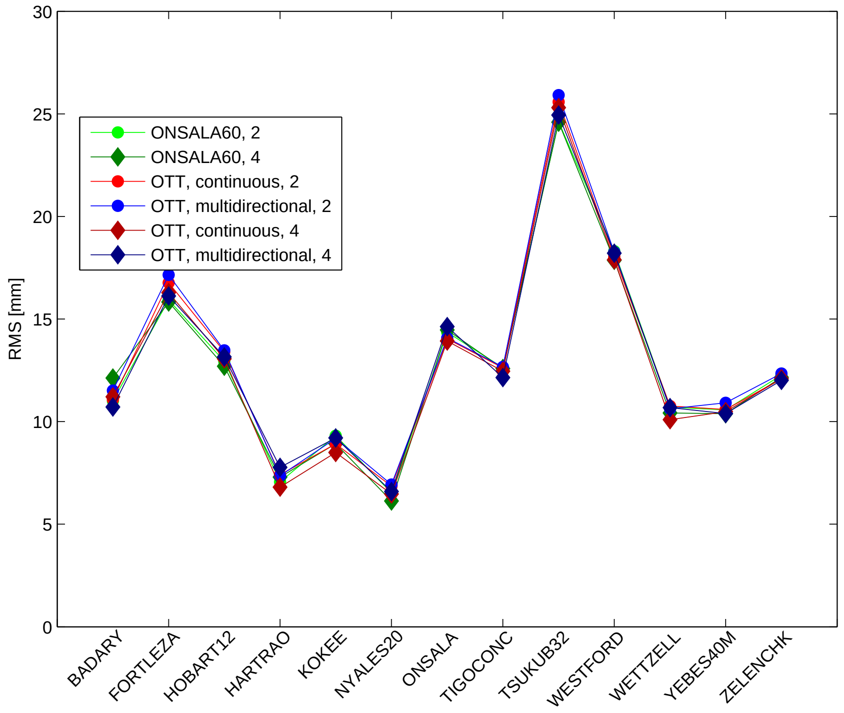

Figure 3.4: RMS of estimated zenith wet delays

Figure 3.4 presents a comparison of RMS values of estimated ZWD for chosen schedules at each CONT11 site. For this purpose estimated ZWD were compared with the simulated ZWD.

The best results at all stations are recieved with 4-SAAT. At 5 stations, the ONSALA60 telescope gains the best results. At the other 8 stations, the OTT is better in resolving the ZWD. At 5 of those 8 stations the continuous mode and at the other 3 the multidirectional mode gains the best result.

For Onsala, the OTT in continuous, 4-SAAT mode obtain the best ZWD values.

All ZWD values are between 6 and 26 mm and the difference in ZWD estimations between the 6 schedules is less than 2 mm at each station.

An indicator for a good ZWD estimation is a good sky coverage, with scans at different elevation angles. Schedules with 4-SAAT have more scans as shown in Figure 3.3 and thence a better ZWD estimation.

3.7 Estimation of station positions - Up, East, North

The estimation of station positions is highly correlated with the distribution of stations in a network and the atmosphere. A good East/West and South/North position is derived by many observations in these directions and the Up position is correlated to the zenith wet delay.

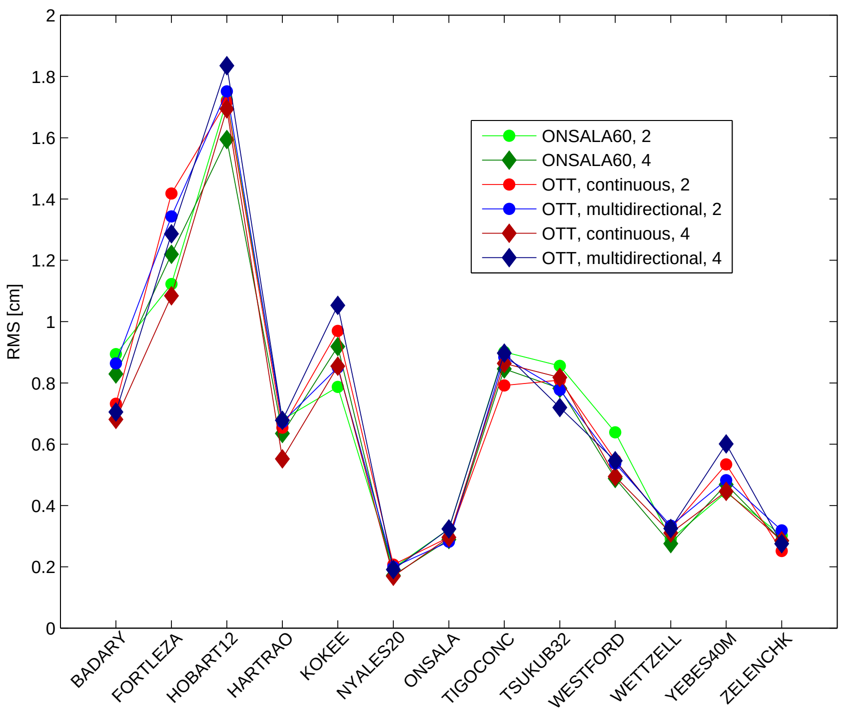

Figure 3.5: RMS for estimated Up position

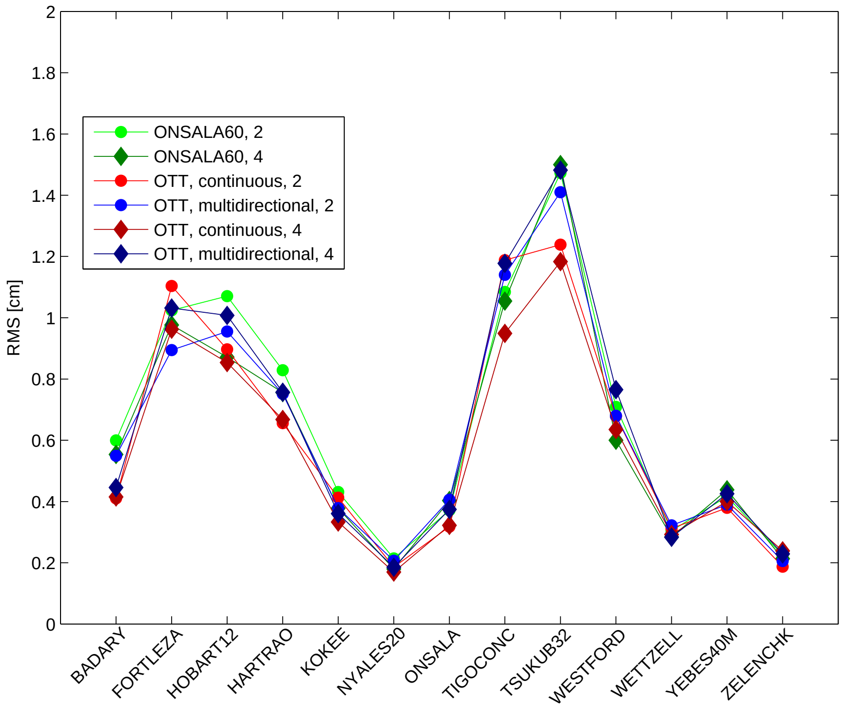

Figure 3.6: RMS for estimated East position

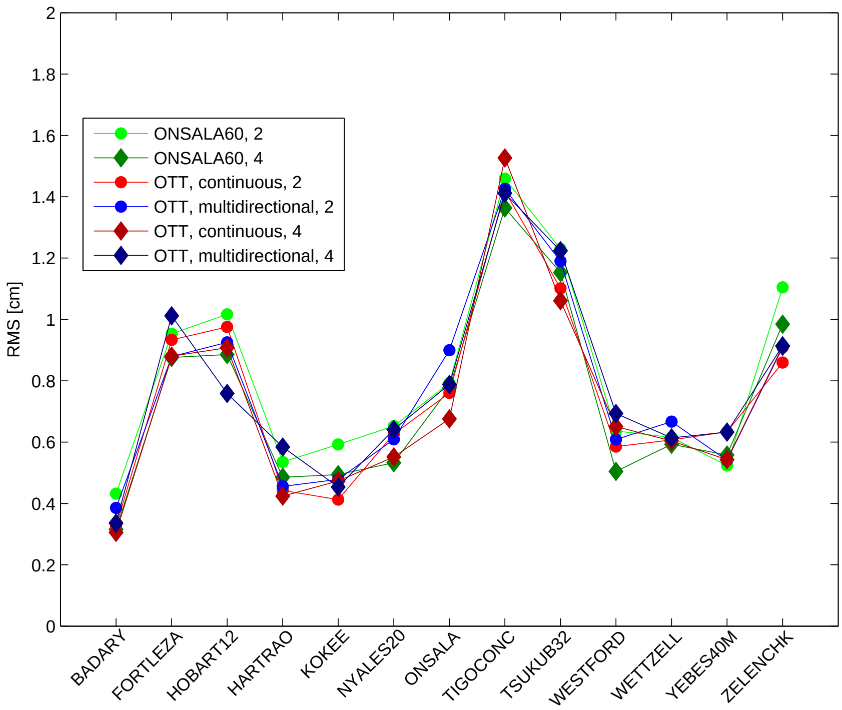

Figure 3.7: RMS for estimated North position

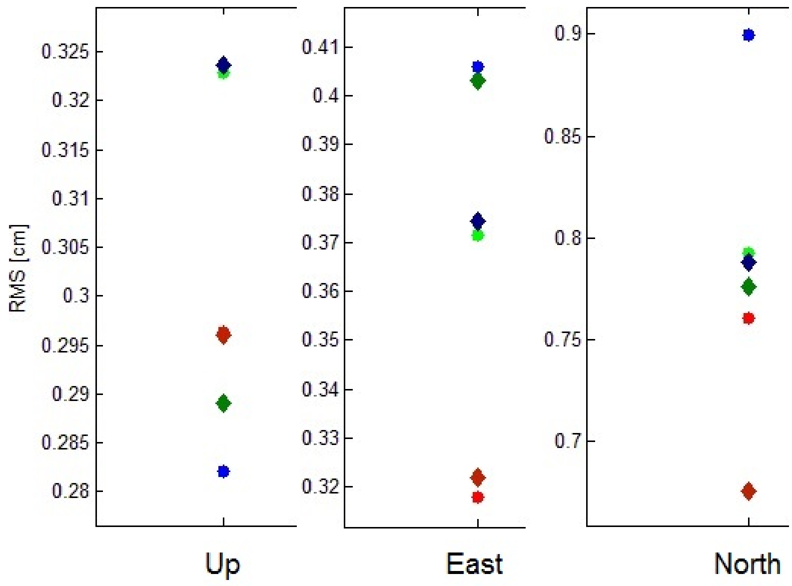

Figure 3.8: A Zoom in on RMS for estimated Up, East and North position in Onslala

Figures 3.5 to 3.7 show RMS of the Up, East and North station positions with a zoom in in Onsala in Figure 3.8.

It is seen, that stations with mostly short baselines have a better East and Up component, i.e. the stations located in or close to Europe (Ny-Ålesund, Onsala, Wettzell, Yebes and Zelenchukskaya). Their RMS is less than 0.5 cm. Those stations form 4-5 baselines with a length shorter than 5000 km. Hobart, which has the worst estimated RMS in the Up direction forms just baselines longer than 8000 km.

The greatest variation in RMS appears in the Up position with values between 0.2 cm and 1.9 cm. Variations in the North and East position are smaller and all RMS are less than 1.6 cm.

In a closer look to Onsala, the Up and East position estimation gives better results than the North position estimation and the continuous mode gives the best results in the East and North position.

On average, the best schedule for station position estimation is the one using the OTT in continuous, 4-SAAT mode. This is also the best schedule, when it comes to baseline length repeatability as shown in Figure 2.6.

3.8 Schedule: OTT, continuous, 4

For a closer look on a particular schedule, the OTT in continuous, 4-SAAT mode was chosen, because of the best results in terms of baseline length repeatability and ZWD estimations as seen in Figure 2.6 and 3.4. Figure 3.9 shows estimations for all three position components for the chosen schedule.

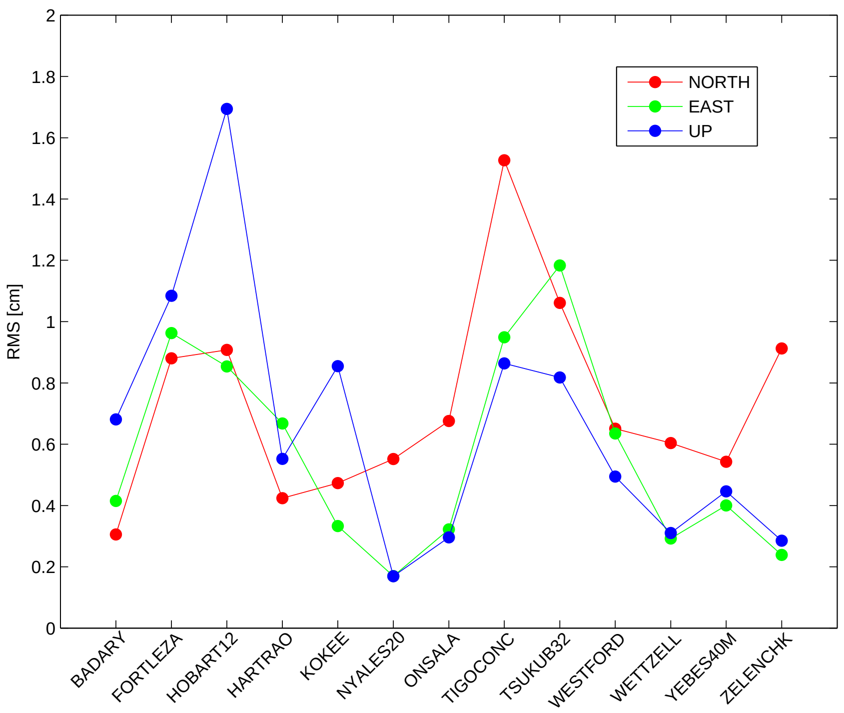

Figure 3.9: RMS for estimated station positions for the the OTT in continuous, 4-SAAT mode

The RMS of all position estimations for this schedule are less than 1.2 cm, except Hobart in the Up position and Tigoconc in the North position. Those telscopes are the smallest in the whole network. No correlation between the 3 components is visible.

3.8.1 Relation between station positions and the number of observations

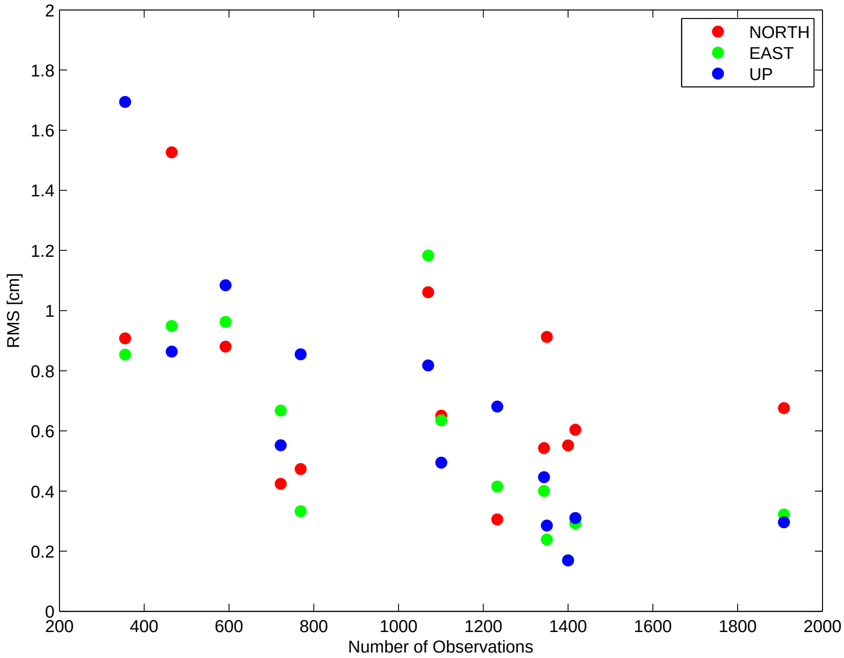

Figure 3.10: RMS for estimated station position versus number of observations

Figures 3.10 shows a slight trend of RMS of station position as a function of number of observations.

The larger the number of observations, the smaller the RMS of the estimated station position. The three dots on the right are the OTT which gain many more observations than the other stations.

3.8.2 Relation between station positions and the number of scans

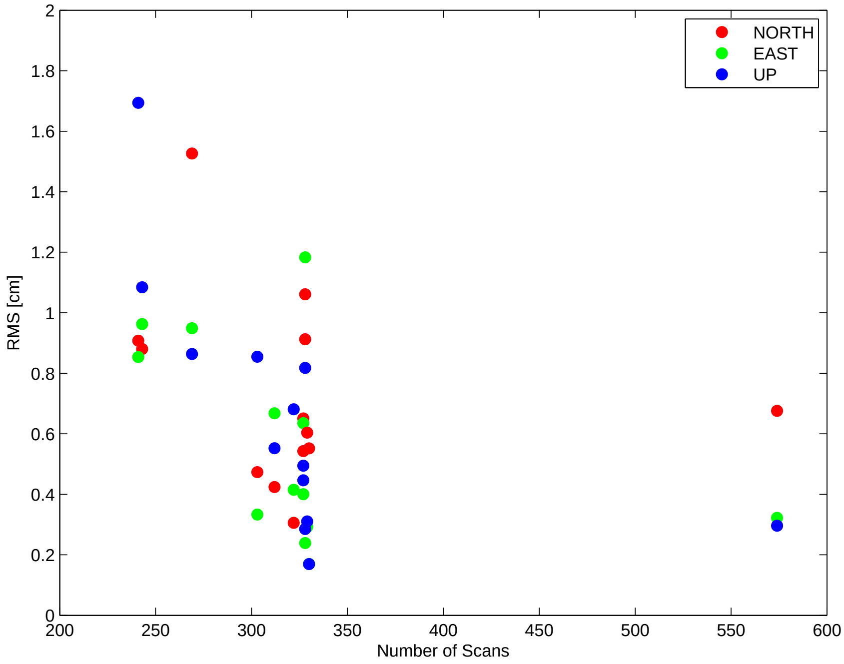

Figure 3.11: RMS for estimated station position versus number of scans

The slight trend shown in Figures 3.10 is even clearer in Figure 3.11, where the RMS of station position is shown as a function of number of scans.

The larger the number of observations, the smaller the RMS of the estimated station position. The three dots on the right are the OTT which gain many more scans than the other stations.

3.8.3 Relation between station positions and RMS of ZWD estimations

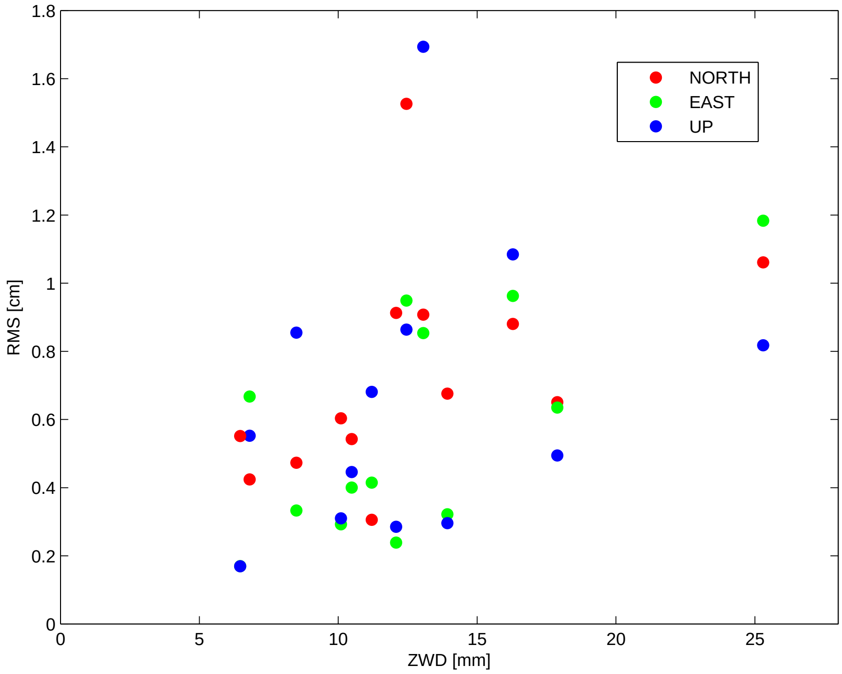

Figure 3.12: RMS for estimated station position versus RMS of ZWD estimation

Figures 3.12 shows a slight trend of RMS of station position as a function of ZWD estimations.

The better the RMS agreement of simulated and estimated ZWD, the better the RMS of the station position estimation.

Therefore the atmosphere is still the limiting factor for geodetic VLBI.

3.9 Estimation of clock offsets

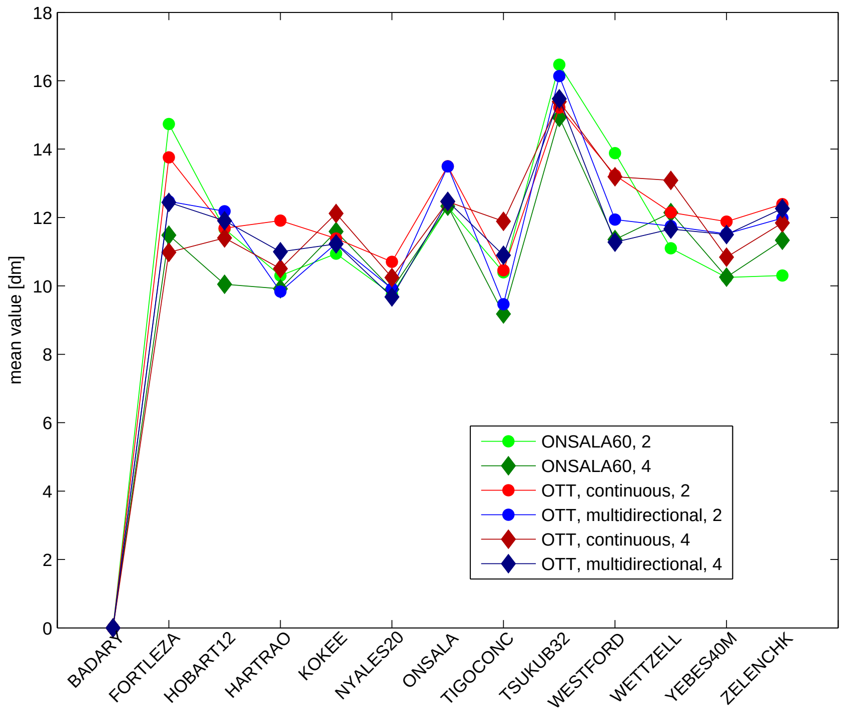

Figure 3.13: mean value of estimated clock offsets

Figure 3.13 shows the mean value of the estimated clock offsets at each station.

Badary was used as a clock reference for those simulations. The effect of clock offsets is on average between 10 dm and 14 dm, except of Tsukuba, where it is between 14 dm and 16 dm. There is no schedule which can be identified to be the best.

3.10 Estimation of Earth Orientation Parameter - EOP

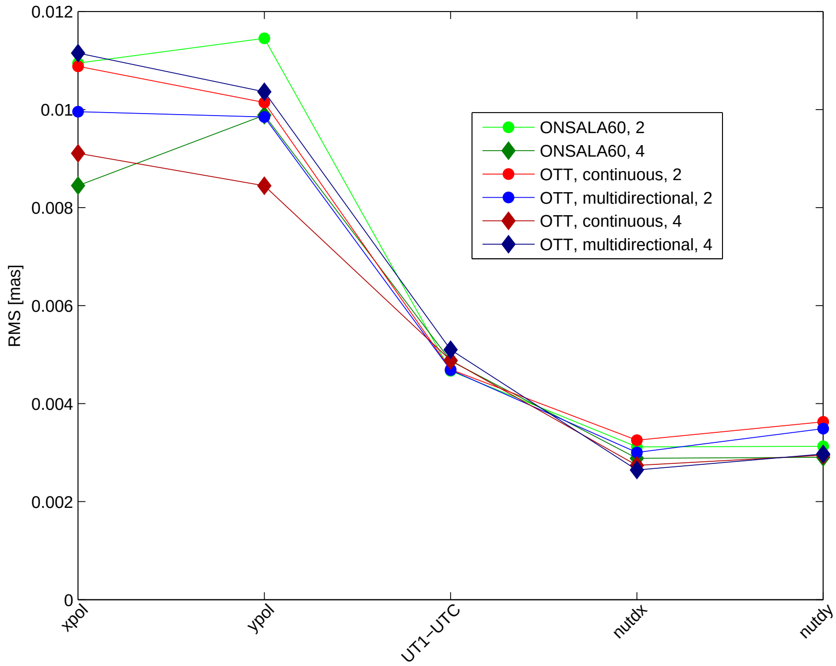

Figure 3.14: RMS for estimated EOP

Figure 3.6 shows a comparison of RMS for chosen schedules for EOP.

It is seen, that estimations for nutation are better than for polar motion. The scale range for nutation is from 0.003 mas to 0.005 mas, while it is between 0.008 mas and 0.012 mas for polar motion.

Furthermore, all schedules with 4-SAAT reach better results than the schedules with 2-SAAT for estimations for nutation and mainly better results for estimations for polar motion.

On the other hand, the 2-SAAT mode is better in UT1-UTC estimations. All UT1-UTC estimations are around 0.005 mas.

Chapter 4

Conclusion

The space observatory in Onsala is very important for geodetic VLBI because of its location in the north. In 2016 the OTT will gradually take over the function of the existing 20 m telescope in Onsala. This is one step to achieve the goals of the VLBI2010 concept with 1 mm in station position and 0.1 mm/yr in station velocity.

In this study a CONT11 network is scheduled, simulated and analysed, with the existing ONSALA60 telescope and the OTT. Comparison of the results show an improvement in estimated parameters with the OTT, especially with the OTT in a continuous mode and a 4 source observed simultaneously strategy.

This schedule recieved the best results in estimations of the ZWD and concerning reference frames and their relative orientation (station position, baseline length repeatability and EOP). It gains the highest number of scans at most stations which is very important for a good sky coverage and thus a good ZWD estimation.

There is a relation between number of observations and station position, number of scans and station position and ZWD estimation and station position. Thus the atmosphere is still the limiting factor for geodetic VLBI.

An OTT with the right schedule strategy improves the whole network in station position accuracy and ZWD estimations. The number of scans and observations naturally increases most in Onsala.

An OTT is one step into the right direction to achieve the goals of the VLBI2010 concept.

Chapter 5

Outlook

A twin telescope initiates a completely new era for VLBI observations and the current equipment and programs have to adapt to the VLBI2010 concept.

At present, the scheduling program SKED is in preparation to schedule Twin Telescopes, but also scheduling options for vie_sched need to be improved.

Current observations and simulations are done in S/X-Band, which will change to broad-band observations to further improve accuracy.

The OTT is expected to operate in 2016 and also other VLBI2010 projects will be realized in the future.

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