In modern geodesy the space-related techniques play an important role. The three most significant of these techniques are the Global Navigation Satellite System (GNSS) that includes the Global Positioning System (GPS), the Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The next generation geodetic VLBI system, VLBI2010, covers everything from antennas to analysis and is being implemented at VLBI stations globally. One of the key requirements for VLBI2010 is the automation of the data analysis in order to reduce the latency of the results to 24 hours.

VLBI is a unique technique for determining the Earth Orientation Parameters (EOP), which are necessary, for example, when calculating satellite orbits. The accuracy of GNSS positioning is related to the accuracy of EOP. Therefore, it is important to measure these parameters with the best possible accuracy and as short latency as possible.

**Improving geodetic VLBI: UT1 accuracy, latency of results, and data quality monitoring**

**Minttu Uunila**
Improving geodetic VLBI: UT1 accuracy, latency of results, and data quality monitoring

Minttu Uunila

A doctoral dissertation completed for the degree of Doctor of Science in Technology to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the Tuas building on 14 June 2013 at 12.

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Abstract

In modern geodesy the space-related techniques play an important role. The three most significant of these techniques are the Global Navigation Satellite System (GNSS) that includes the Global Positioning System (GPS), the Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The next generation geodetic VLBI system, VLBI2010, covers everything from antennas to analysis and is being implemented at VLBI stations globally. One of the key requirements for VLBI2010 is the automation of the data analysis in order to reduce the latency of the results to 24 hours.

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In this dissertation the automation of the International VLBI Service for geodesy and astrometry (IVS) intensive sessions is described. In the near future, the Vienna VLBI Software (VieVS) will be implemented with the pre-analysis steps that are currently being developed, the group delay ambiguity resolution and the ionospheric correction. The most commonly used geodetic VLBI analysis software is Calc/Solve that is maintained at the Goddard Space Flight Center (GSFC). So as not to bias the outcome by adopting only one software package, a comparison of Solve and VieVS EOP results was performed. This comparison showed that VieVS analysis appeared to improve the accuracy in the dUT1 result. However, polar motion results were more precise when Solve was used for the analysis.

To fulfill the VLBI2010 precision requirements, the effect of source distribution on the dUT1 result accuracy obtained from IVS INT1 experiments was investigated. On the basis of the research conducted in this thesis, the results from the source constellation study show that the accuracy of the dUT1 is affected by the distribution in the sky as seen from the midpoint of a baseline, and will improve when a novel method proposed for scheduling intensive sessions will be implemented. Until now, the sky has been observed from the Kokee Park North direction. Introducing the new concept of observing the sky from a fictitious midpoint of the baseline greatly improves dUT1 accuracy. IVS should take this into consideration, because the accuracy of the results is a significant factor when calculating satellite orbits, for example.

VLBI2010 requires shipment of the VLBI data via Internet. Firmware was developed to enable VLBI2010-compatible stations to perform zero baseline correlation tests with the Digital Base Band Converter (DBBC) and FILA10G ethernet board, and thus the stations can check the quality of the data in real-time.

Keywords  VLBI, geodesy, UT1, VHDL
Tiivistelmä


Jotta VLBI2010-tarkkuusvaatimukset voitaisiin täyttää, tutkittiin dUT1-tuloksia IVS:n INT1-sessioista. Oletuksena oli, että lähteiden sijainti taivaalla kahta teleskooppia yhdistävän viivan keskipisteestä nähtynä vaikuttaa parametriin ja sen virheeseen. Tutkimuksessa todettiin, että ne sessiot, joissa kohteet olivat mahdollisimman kaukana toisistaan, tuottivat tarkimmat tulokset.

Väitöskirjatutkimuksessa kirjoitettiin VHDL-firmware niin kutsuttuja ‘zero baseline correlation’-testejä varten, joiden avulla voidaan tutkia VLBI-datan laatua.
This work was conducted at Aalto University Metsähovi Radio Observatory, and included a four-month research visit to Max Planck Institute for Radio astronomy (MPIfR) in 10/2011 - 1/2012. The work was carried out in the ‘eVLBI+geo: From ultrarapid data transfer into science - near realtime VLBI application’ project funded by the Computational Science Research Programme called Lastu of the Academy of Finland (grant number 135101).

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Thank you Dr. Kevin Douglas for his suggestions to improve my grammar. You must be the only one who can make correcting ones own mistakes fun. From now on I will remember that 'every for example needs commas to hug it'. Thank you Dr. Diana Hannikainen for the second proof-reading.

I wish to thank my parents for their endless support, and encouraging me to get a Bachelor's degree in electronics, a Master's degree in astronomy, and a PhD in space technology. I'll promise to stop studying now!

Thank you Miikka for your love, and enabling my scientific career by staying home with our sons when I returned to work. Thank you Otava and Jouka for giving me a new perspective in life, and making me a greater person.

'Multa ylläni
hauraana, harson lailla.
Näin avaruuden katseen
salaisuuksia vailla.’
- Uuno Kailas

'Kauan kulkenut oon
Minä tähtien teitä
Ja tähdet minua varjelkoon
Kun tuulessa Tuoni tuoksuu’
- Kaarle Viikate

Helsinki, April 26, 2013

Minttu Uunila
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<th>Description</th>
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<tbody>
<tr>
<td>AAM</td>
<td>Atmospheric Angular Momentum.</td>
</tr>
<tr>
<td>AD</td>
<td>Analog-to-Digital.</td>
</tr>
<tr>
<td>ARAIC</td>
<td>Ambiguity Resolution And Ionospheric Correction.</td>
</tr>
<tr>
<td>BBC</td>
<td>Baseband Converter.</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off The Shelf.</td>
</tr>
<tr>
<td>CRF</td>
<td>Celestial Reference Frame.</td>
</tr>
<tr>
<td>DAS</td>
<td>Data Acquisition System.</td>
</tr>
<tr>
<td>DBBC</td>
<td>Digital Baseband Converter.</td>
</tr>
<tr>
<td>DDC</td>
<td>Digital Down Converter.</td>
</tr>
<tr>
<td>DORIS</td>
<td>Doppler Orbitography and Radiopositioning Integrated by Satellite.</td>
</tr>
<tr>
<td>dUT1</td>
<td>UT1-UTC.</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-range Weather Forecasts.</td>
</tr>
<tr>
<td>EOP</td>
<td>Earth Orientation Parameter.</td>
</tr>
<tr>
<td>EVN</td>
<td>European VLBI Network.</td>
</tr>
<tr>
<td>FE</td>
<td>Formal Error.</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transformation.</td>
</tr>
<tr>
<td>FGI</td>
<td>Finnish Geodetic Institute.</td>
</tr>
<tr>
<td>FILA</td>
<td>First and Last.</td>
</tr>
<tr>
<td>FILA10G</td>
<td>First and Last ten gigabit ethernet board.</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite Impulse Response.</td>
</tr>
<tr>
<td>FPGA</td>
<td>Fully Programmable Gate Array.</td>
</tr>
<tr>
<td>FS</td>
<td>Field System.</td>
</tr>
<tr>
<td>GE</td>
<td>Giga-bit Ethernet.</td>
</tr>
<tr>
<td>GMF</td>
<td>Global Mapping Function.</td>
</tr>
<tr>
<td>GMVA</td>
<td>Global Millimeter VLBI Array.</td>
</tr>
<tr>
<td>GSI</td>
<td>Geospatial Information authority of Japan.</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface.</td>
</tr>
<tr>
<td>HSI</td>
<td>High Speed Interface.</td>
</tr>
</tbody>
</table>
ICRS  International Celestial Reference System.
IERS  International Earth Rotation and Reference Systems Service.
IF    Intermediate Frequency.
IGG   Institute of Geodesy and Geoinformation, University of Bonn.
INAF  National Institute for Astrophysics.
IP    Internet Protocol.
ITRF  International Terrestrial Reference Frame.
ITRS  International Terrestrial Reference System.
JPL   Jet Propulsion Laboratory.
LCP   Left Circular Polarization.
LLR   Lunar Laser Ranging.
LOFAR LOw Frequency ARray.
MPIfR Max Planck Institute for Radio astronomy.
NASA  National Aeronautics and Space Administration.
NEXPreS Novel EXplorations Pushing Robust e-VLBI Services.
NGS   National Geodetic Survey.
NRAO  National Radio Astronomy Observatory.
OSO   Onsala Space Observatory.
PFB   Polyphase Filter Bank.
PPS   Pulse Per Second.
RCP   Right Circular Polarization.
RDBE  Roach Digital Backend.
RF    Radio Frequency.
RFI   Radio Frequency Interference.
RMS   Root Mean Square.
SEFD  System Equivalent Flux Density.
SKA   Square Kilometer Array.
TRF   Terrestial Reference Frame.
TU Vienna Vienna University of technology.
UDP   User Datagram Protocol.
USNO  U.S. Naval Observatory.
UT    Universal Time.
UT1   principal form of Universal Time.
UTC   Universal Time Coordinated.
VDIF  VLBI Data Interchange Format.
VHDL  VHSIC Hardware Description Language.
VHSIC Very High Speed Integrated Circuits.
VLBA  Very Long Baseline Array.
List of Abbreviations

VMF1 Vienna Mapping function.
VSI VLBI Standard Interface.
WRMS Weighted Root Mean Square.
Xpol polar motion in the X direction.
Ypol polar motion in the Y direction.
ZWD Zenith Wet Delay.

Station Codes mentioned in the thesis

Bd Badary
Eb Effelsberg
Ft Fortaleza
Hb Hobart12
Hh Hartrao
Ho Hobart26
Ke Katherine
Kk Kokee
Ma Matera
Mc Medicina
Mh Metsähovi
Ny Ny Ålesund
On Onsala
Sv Svetloe
Tc Tigo Conception
Ts Tsukuba
Wf Westford
Ww Warkworth
Wz Wettzell
Yg Yarragadee
Ys Yebees
Zc Zelenchkukskaya
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i$</td>
<td>Clock function coefficients ($a_0 - a_2$).</td>
</tr>
<tr>
<td>$b$</td>
<td>Baseline length.</td>
</tr>
<tr>
<td>$b_0$</td>
<td>Clock function coefficient.</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light.</td>
</tr>
<tr>
<td>$C_{xy}$</td>
<td>Cross correlation function.</td>
</tr>
<tr>
<td>$D$</td>
<td>Elongation of the Moon from the Sun.</td>
</tr>
<tr>
<td>$e$</td>
<td>Mathematical constant, that is the base of the natural logarithm.</td>
</tr>
<tr>
<td>$F$</td>
<td>Argument of latitude of the Moon.</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency.</td>
</tr>
<tr>
<td>$G$</td>
<td>Gravitational constant.</td>
</tr>
<tr>
<td>$l$</td>
<td>Mean anomaly of the Moon.</td>
</tr>
<tr>
<td>$l'$</td>
<td>Mean anomaly of the Sun.</td>
</tr>
<tr>
<td>$l, h$</td>
<td>Love numbers.</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass.</td>
</tr>
<tr>
<td>$M_d$</td>
<td>Molar weight of dry air.</td>
</tr>
<tr>
<td>$m f$</td>
<td>Mapping function.</td>
</tr>
<tr>
<td>$P_n(\cos\theta)$</td>
<td>Legendre polynomials.</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Ground pressure.</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant.</td>
</tr>
<tr>
<td>$s_i(\nu)$</td>
<td>Station spectra.</td>
</tr>
<tr>
<td>$S_{ij}(\nu)$</td>
<td>Cross multiplied station spectra.</td>
</tr>
<tr>
<td>$V_i$</td>
<td>Astronomical argument of $i$.</td>
</tr>
<tr>
<td>$x$</td>
<td>Polar motion in x direction.</td>
</tr>
<tr>
<td>$y$</td>
<td>Polar motion in y direction.</td>
</tr>
<tr>
<td>$\Delta X$</td>
<td>Change in the baseline component in direction X caused by polar motion.</td>
</tr>
</tbody>
</table>
List of Symbols

\( \Delta Y \) Change in the baseline component in direction Y caused by polar motion.

\( \Delta Z \) Change in the baseline component in direction Z caused by polar motion.

\( X(f)Y^*(f) \) Cross spectrum of the telescopes X and Y.

\( \Delta \rho_{\text{ion}} \) Ionospheric path delay.

\( \delta \) Ocean loading.

\( \theta \) Angle of the plane front arriving at the stations.

\( \theta_{\text{dUT1}} \) Earth rotation parameter dUT1.

\( \pi \) Mathematical constant that is the ratio of a circle’s circumference to its diameter.

\( \tau \) Delay, time difference.

\( \tau_c \) Delay caused by errors in the synchronization of the telescope reference clocks.

\( \tau_g \) Geometric delay.

\( \tau_{\text{inst}} \) Delay caused by the signal propagation through the antenna instrumentation and cables.

\( \tau_{\text{ion}} \) Delay in the signal propagation time caused by the ionosphere.

\( \tau_{\text{obs}} \) Observed delay.

\( \tau_{\text{rel}} \) Delay arising from general and special relativistic corrections to the geometric delay.

\( \tau_{\text{trop}} \) Delay in the signal propagation time caused by the troposphere.

\( \phi \) Phase.

\( \varphi_i \) Tide.

\( \varphi_{ij} \) Greenwich phase lag.

\( \omega \) Circular frequency.

\( \Omega \) Longitude of the ascending lunar node.
1. Introduction

1.1 Background

Geodesy measures and represents the Earth and its gravity field, as well as its motion, and orientation in space. Modern geodesy relies on space-based observing systems. One of the three most important techniques is Very Long Baseline Interferometry (VLBI), the other two being the Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR).

In VLBI two or more radio telescopes measure the same distant sources at the same time. Radio telescopes are usually parabolic antennas, which may differ in size and build. The next generation geodetic VLBI system, VLBI2010 [1], prefers small, fast slewing 10-12 m diameter telescopes that enable the rapid movement of the telescope from source to source. In geodetic VLBI, active galaxies known as quasars are observed since they are so distant and hence do not appear to change position when observed from Earth, effectively acting as point sources. However, when the coordinate accuracy for VLBI2010 is required to be 1mm, the structure of sources needs to be considered. If, for example, jets are involved, then the structure of the quasar varies, and this in turn will affect the accuracy of the results.

The relation between the Celestial Reference Frame (CRF) and Terrestrial Reference Frame (TRF) is determined by the Earth Orientation Parameters (EOPs), which fix the Earth’s rotation axis with respect to the CRF, time correction, the difference between UT1-UTC (dUT1) and by the polar motions (polar motion in the X direction (Xpol) and polar motion in the Y direction (Ypol)), which fix the Earth’s crust. The CRF and TRF are described in detail in Chapter 2.

The Earth rotation is described by the dUT1 parameter, which is the
difference between the time scales provided by the Earth’s own rotation described by principal form of Universal Time (UT1), and the one provided by atomic clocks, Universal Time Coordinated (UTC) [2]. Earth's rotation, for example, is slowed down by the tides caused by the Moon. Other factors that affect rotation are the re-distribution of mass within the earth, oceans, and the atmosphere, as well as powerful earthquakes.

With VLBI the positions and velocities of the stations and the EOPs (dUT1, nutation, precession and polar motion) can be measured accurately. Nutation is caused by the tidal force of the Moon that in turn disturbs the precession. Polar motion is the movement of the Earth's rotational axis across the Earth's surface. In addition to these, VLBI is the only technique capable of defining the inertial reference system, the CRF, by observing quasars billions of light years away.

What makes geodetic VLBI important is its unique ability to determine the orientation of the Earth with the dUT1 and nutation parameters. The International VLBI Service for geodesy and astrometry (IVS [3]) observes dUT1 weekly with two different types of experiments, the intensive sessions and the 24-hour sessions. The intensive sessions have East-West oriented baselines, and the experiments are especially designed to determine dUT1. The 24-hour sessions, called R1 and R4, are designed to measure all the Earth Orientation Parameters (EOPs), including dUT1, nutation and polar motion. Earth orientation and the dUT1 parameter are required when satellite orbits are calculated in the inertial coordinate system, and when the CRF needs to be tied to the TRF.

1.2 Scientific purpose

The motivations for the thesis are listed below. The research conducted consists of four separate parts:

1. One of the aims was to ensure that the EOP, dUT1, and polar motion results from the Vienna VLBI Software (VieVS [4]) analysis are comparable with the ones from the most commonly used geodetic VLBI analysis software, Calc/Solve [5]. Both software packages were run using their default setups. To bring Solve and VieVS results as close as possible, a special configuration of both software packages was planned, and as many of the models, a priori files and software-related setups were chosen to be the same for both of the packages.
2. One of the most important scientific purposes of the thesis was to show that special attention needs to be given to scheduling the IVS intensive sessions. It was necessary to distinguish how the source distribution affects the accuracy of the Earth rotation parameter dUT1 results when the reference point was the midpoint of the baseline. From these results a recommendation for the International VLBI Service for geodesy and astrometry (IVS [3]) will be given, to be used as a guideline in scheduling IVS intensive sessions to obtain the most accurate dUT1 results. The dUT1 parameter is needed, for example, when deriving GPS satellite orbits, and the accuracy of the GPS orbits is directly related to the accuracy of the user-determined position\(^1\). Thus the accuracy of the dUT1 is highly important.

3. The third aim of the thesis was to analyze IVS intensive sessions automatically with the Vienna VLBI Software (VieVS) by using Matlab in its batch mode. The purpose of the research was to enable faster determination of the Earth Orientation Parameter (EOP) dUT1 with the Vienna VLBI Software (VieVS [4]) by automating the analysis of the IVS intensive sessions, INT1, INT2 and INT3. Three different strategies for different modeling options were also tested, and their effect on the latency of the results examined. Weighted Root Mean Square (WRMS) values were calculated and dUT1 graphs for different strategies were created. WRMS values and the graphs were plotted automatically on the Metsähovi web site.

One goal of the thesis was to start the work required for using the VieVS independently from Calc/Solve, by introducing the missing pre-analysis steps, the ambiguity resolution, and the ionospheric correction that needed to be added to the software. The implementation was started in that a Graphical User Interface (GUI) and a preliminary Matlab script for analyzing intensive sessions was written. When the implementation is ready, it will reduce the latency of the results, which is one of the main purposes of the next generation VLBI system, VLBI2010, and automating the analysis also of the 24-hour sessions will be possible.

4. The last of the aims was to enable VLBI stations to check the functionality of a Digital Baseband Converter (DBBC [6]), and to moni-

\(^1\)http://www.noaa.gov/orbits/
tor the quality of the data at VLBI stations. Using Very High Speed Integrated Circuits (VHSIC) VHSIC Hardware Description Language (VHDL), firmware was written that can be run within the Fully Programmable Gate Array (FPGA) inside the First and Last ten gigabit ethernet board (FILA10G) board. When VLBI2010 is deployed and data transferred via the Internet instead of shippable disk modules, the firmware will be of great importance.

The next generation VLBI system, VLBI2010 [1], requires improvements from antennas to analysis, and in this thesis three of these requirements were examined. Improving the accuracy of the dUT1 parameter is a key requirement, also the analysis needs to be at least partly automated to reduce the latency of the results to less than 24 hours, and this can be done by automating the VieVS analysis software. Implementing VieVS with the pre-analysis steps currently being developed will help in making the automation of 24-hour sessions possible in the near future. VLBI2010 also requires the VLBI backends to be digital to improve the resolution. If the VLBI data are transferred via the Internet, instead of using shippable disk modules, the latency of the results is further reduced because the data can be correlated in near real time. One of the aims of the thesis is to enable the user at a VLBI station with a Digital Baseband Converter (DBBC [6]) to use a FILA10G board firmware to ensure the functionality of a DBBC, and to monitor the quality of the data. Special firmware was written to enable these auto-correlation check-ups of the system. The firmware will be used inside the FPGA circuit in the FILA10G board after final testing.

1.3 Outline of the thesis

• Chapter 2 introduces the Very Long Baseline (VLBI) technique, its history, the basic concept, and the observables. Geodetic VLBI is described.

• Chapter 3 describes materials and methods. The VLBI equipment - radio telescopes, receivers, hydrogen masers, backends, formatter and recorders - are described in addition to the field system, e-transfer and Metsähovi Radio Observatory’s equipment, and the networks the station belongs to, are described.

The International VLBI Service for geodesy and astrometry (IVS [3]) is
introduced, and its weekly and other sessions described. The most commonly used geodetic VLBI analysis software, as well as the concept of the next generation geodetic VLBI system, VLBI2010 [1], are described.

- In Chapter 4 the results of four different research projects are given.

  1. The UT1 and polar motion comparison results derived from IVS sessions from VieVS [4] and Solve [5] analysis are presented.

  2. The effect of source distribution in the sky on the accuracy of UT1 derived from the IVS INT1 sessions is studied.

  3. The automation of the Vienna VLBI Software (VieVS [4]) for deriving UT1 from the IVS [3] intensive sessions is performed. The implementation of the group delay ambiguity resolution and ionospheric correction to VieVS [4] are studied.

  4. The VHDL firmware for zero baseline tests to be performed with the FX correlator inside the FILA10G board of the Digital Baseband Converter (DBBC [6]) was written.

- In Chapter 5 conclusions are drawn and future work is suggested.

### 1.4 Contribution of the author

- The analysis software comparison results from the VieVS and Solve software for the VieVS analysis part were conducted by the author. The Matlab scripts for comparing the two sets of results and for their visualization were also written by the author. The Calc/Solve analysis was conducted by Karen Baver from NVI/ National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC). Other contributors were John Gipson from NVI / NASA GSFC and Tobias Nilsson from the Institute of Geodesy and Geophysics, the Vienna University of technology (TU Vienna), who both helped with the parameterization of the software packages.
The author created a Matlab code for dividing the sky seen from the midpoint of the Wettzell-Kokee baseline, into six sections, to give quality codes to IVS INT1 sessions. The Matlab code was used to produce different plots, and to visualize results from the data analysis performed by the author with Vienna VLBI Software (VieVS). The idea to include the number of scans per session came from the author. Other contributors for the research were Axel Nothnagel, who had the idea to undertake this study, and Judith Leek, from the Institute of Geodesy and Geoinformation, University of Bonn, who wrote the SkyPlot program. Part of this work was performed during a four-month research visit to Max Planck Institute for Radio astronomy (MPIfR) in Bonn, Germany.

The author designed the parameter files on the basis of her VieVS analysis results, the outline of the automation code, and partly designed the presentation of the UT1 plots. Other contributors to this work were Rüdiger Haas from Chalmers University of Technology, and Niko Kareinen and Timo Lindfors, both from from Metsähovi Radio Observatory, Aalto University. Rüdiger Haas had the idea to improve the latency of the dUT1-results by automating VieVS, Niko Kareinen produced the script for visualizing the data, while Timo Lindfors wrote the automation script, under supervision of the author.

The Graphical User Interface (GUI) designed for implementing ambiguity resolution and ionospheric correction for VieVS was written by the author. The author also partly contributed in the Matlab script to read National Geodetic Survey (NGS) files, to perform the ambiguity resolution, and apply ionospheric correction. Rüdiger Haas suggested implementing these steps into VieVS, and is mostly responsible for the ambiguity resolution part. The author is going to finish other parts of the research in the near future in collaboration with Rüdiger Haas.

The VHDL code written for zero baseline tests within the FILA10G board inside the Digital Baseband Converter (DBBC) was written by the author in collaboration with Gino Tuccari from INAF. The functionality implemented by the code is a useful contribution to assure that the backends present in the radiotelescopes, typically very far from one another, are coherently able to process signals received with the interferometric VLBI method. Part of this work was performed during a four-month research visit to MPIfR in Bonn, Germany.
2. Very Long Baseline Interferometry

2.1 History of VLBI

In Very Long Baseline Interferometry (VLBI) two or more radio telescopes observe the same distant source in the sky at the same time. The telescopes form an interferometer of size equivalent to the maximum length between the stations. The data are time tagged with a 1 Pulse Per Second (PPS) signal from an accurate hydrogen maser, and recorded with a Data Acquisition System (DAS). Data from the different stations are sent, either in disk modules or by e-transfer via the Internet, to the correlator, where the data are combined. VLBI, from a geodetic point of view, is a unique technique in its ability to measure the orientation of the Earth in an inertial reference frame.

Interferometric techniques in astronomy date back to the optical work by Michelson [7] [8] and Michelson and Pease [9] who were able to measure the diameters of, for example, Arcturus and Betelgeuse with sufficiently fine angular resolution.

The history of VLBI starts with the discovery of radio astronomy. Karl Jansky was the first to discover celestial radio emission, and he was the first to build a radio telescope for detecting a radio source in 1931 [10]. Grote Reber, an amateur radio operator, was the first person to design a parabolic radio telescope six years later [11]. Reber constructed the first maps of radio emission of the Milky Way at frequencies of 160 and 480 MHz [12]. After the second World War the field expanded by taking advantage of the development of radar technology [13] [14]. The technique of radio interferometry was pioneered in 1946, and Martin Ryle’s group [15] in Cambridge was later awarded a Nobel Prize for their contribution to interferometry and aperture synthesis. The Lloyd’s mirror interferom-
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er was also developed independently in 1946 by Joseph Pawsey’s group [16] at the University of Sydney. In the early 1950s the Cambridge Interferometer [17] [18] mapped the radio sky to produce the famous 2C and 3C surveys [19] of radio sources. A revised version of the 3C catalog [20] became the cornerstone of radio astronomy for the following decade [21].

The largest array, the LOw Frequency ARray (LOFAR)\(^1\), is currently being constructed in western Europe, consisting of about 20 000 small antennas in 48 stations distributed over an area several hundreds of kilometres in diameter, and operates between 1.25 and 30 m wavelengths. The world’s largest physically connected telescopes, the Square Kilometer Array (SKA), is planned to start operation in 2020 [22].

The possibility of using VLBI for geodesy was realized in 1967 by Gold [23], and investigated by Shapiro and Knight in 1970 [24]. Their expectations, and research ideas were:

1. effective wide-bandwidth techniques for making precision phase-delay measurements over intercontinental baselines, global geodesy;
2. precision determination of global geodetic ties;
3. crustal-block motions including continental drift;
4. polar motion;
5. Earth rotation;
6. refinement of values for the precession and nutation constants, including a test of general relativity;
7. rate of change of obliquity of the ecliptic (obliquity is the axial tilt between the equatorial and orbital planes);
8. measurements of the shape of the sea surface;
9. determination of the geopotential;
10. global time synchronization.

In their paper they describe the basic technique for geodetic VLBI, the limitations on accuracy, useful antenna systems and sources of radiation, as well as geophysical applications. Their research ideas are still being studied in modern geodesy, for example EOPs are the main observables of the IVS in its weekly sessions, and the shape of the sea surface is monitored accurately due to the ice sheets melting as a result of climate change.

\(^1\)http://www.lofar.org
The first intercontinental geodetic VLBI measurement was conducted in 1969 with the baseline Haystack - Onsala [25]. One-hour one baseline intensive sessions scheduled for UT1 determination have been measured routinely since 1984. The first baseline was Wettzell - Westford, but now Wettzell - Kokee Park is used. A second baseline, Wettzell - Tsukuba, for intensive sessions was established in 2002 [26]. In the present day geodetic VLBI aims to determine both the Terrestrial and Celestial Reference Frames (TRF and CRF) by measuring the station coordinates and velocities, and radio source positions. Other observables are the Earth Orientation Parameters (EOPs) and geodynamical parameters.

2.2 Basic concept of VLBI

Radio interferometry’s primary purpose for astronomy is to increase the angular resolution. This is done with a technique called aperture synthesis, which works by interfering the signal waves from the different telescopes. The radio waves that coincide in phase will add to each other while two waves that have opposite phases will cancel each other out. A combined telescope is thus created and it is equivalent in resolution (though not in sensitivity) to a single antenna whose diameter is equal to the spacing of the antennas furthest apart in the array. The basic concept of VLBI is displayed in Figure 2.1.

![Figure 2.1. Basic concept of VLBI.](image-url)
The basic observable in geodetic VLBI is the group delay, resulting from a plane wavefront from a distant quasar that has different arrival times at two telescopes. The delay is described in Equation 2.1 [21]:

\[ \tau = \frac{1}{c} \times b \times \cos \theta \] (2.1)

where \( \tau \) is the time difference (delay), \( c \) is the speed of light, \( b \) is the baseline length, and \( \theta \) is the arrival angle of the wavefront at the stations. The accuracy with which the group delay can be measured is a fraction of the reciprocal bandwidth [21].

At the geodetic VLBI stations several steps need to be performed independently:

1. Down-conversion of the high frequency band intervals’ (8 and 2 GHz) signals to video frequencies (0-500 MHz);
2. Analog-to-digital conversion with 1-bit sampling for geodesy (conserves phase information, but the amplitude information is lost);
3. Adding a time tag from an H-maser;
4. Formatting and recording of the data;
5. Sending the data by e-transfer via the Internet, or shipping of a module of hard disks to the correlator.

At the correlator (for example the Bonn Correlator at the Max Planck Institute for Radio astronomy, the Haystack correlator, or the Washington correlator), the raw data are played back, coarse synchronization using \textit{a priori} information is performed, cross correlation of the bit streams is conducted, maximum correlation is searched for, and determination of the delay observables is performed. \( C_{xy} \) is the cross correlation function, and is given in Equation 2.2 [21]:

\[ C_{xy}(\tau) = \int_{-\infty}^{+\infty} X(f)Y^*\left(f\right)e^{i2\pi f\tau} df \] (2.2)

where \( \tau \) is the delay between the two telescopes, \( X(f)Y^*(f) \) is the cross spectrum of the telescopes X and Y, and \( f \) is the frequency. A maximum likelihood estimation is applied to a data set and given a statistical model, after which estimates for the model’s parameters are provided. In the time domain this corresponds to minimizing the correlation function, and in the frequency domain, maximizing the cross spectrum.
When the cross correlation function is investigated for a single video channel, it has three terms: the first is due to changing geometry, the second a Doppler effect, and the third a relative phase between the local oscillators at the stations. The cross correlation functions can be normalized with autocorrelation functions.

In correlator processing, delay tracking and fringe stopping are performed. The first means that the delay needs to be monitored by adjusting steps of 1-bit in a manner such that the error is within +/- 0.5 bits. The latter means that to enable successful correlation, the Doppler shift effects caused by Earth rotation need to be compensated. Another requirement for a successful correlation is the use of appropriate \textit{a priori} values for the delay and the delay rate.

So-called raw correlator output includes normalized cross-correlation functions for each baseband, signal-to-noise, and phase calibration information. The term baseband describes a signal and a system which have a frequency range from close to 0 Hz to a cut-off frequency, defined with a lowpass filter. A sharp cut-off at the zero frequency of the baseband can be achieved by the use of a single-sideband mixer for the conversion to baseband [21]. These are used for the correlator post-processing for the coarse and precise delay search. Final post-correlation output includes the group delay, and the delay rate observations, timing, signal to noise, and station related information. The group delay can be derived from the position of the correlation peak, the slope of the cross power spectrum phase versus frequency, and a Fourier transform of the cross correlation, which is a function of $\tau$ [21]. Delay rate is the fringe frequency that varies with the hour angle of the observed source [21].

\section{2.3 Geodetic VLBI}

In the following sections the main geodetic observable, the geometrical delay, is explained, and the applications of geodetic VLBI are described.

\subsection{2.3.1 Geometrical delay}

The geometrical delay $\tau_g$ is the fundamental observable, and is the first derivative of the phase delay. When the group delay is used instead of the phase delay, the accuracy suffers but there are no ambiguities. Because the group delay contains a systematic delay from the ionosphere, geodetic
VLBI observations are always recorded with a dual S/X frequency, as the S band is used to remove the effect of the ionosphere.

The observed time delay $\tau_{obs}$ is given by Equation 2.3 [27]:

$$\tau_{obs} = \tau_g + \tau_c + \tau_{ion} + \tau_{trop} + \tau_{inst} + \tau_{rel} + \ldots,$$

(2.3)

The observed time delay consists of the geometric delay, $\tau_g$, and the perturbation terms, which include:

• $\tau_c$, the delay caused by errors in the synchronization of the telescope reference clocks and clock drifts;

• $\tau_{ion}$, the delay in the signal propagation time caused by the ionosphere;

• $\tau_{trop}$, the delay in the signal propagation time caused by the troposphere. The stratosphere causes significant contributions of about 20-30 %;

• $\tau_{inst}$, the delay caused by the signal propagation through the antenna instrumentation and cables;

• $\tau_{rel}$, the delay arising from general and special relativistic corrections to the geometric delay.

Baseline corrections [25], which have a range from a couple of mm per day to several dm per day (solid Earth tides), in the TRF include:

• Solid Earth tides with diurnal and semidiurnal amplitudes of several dm;

• Plate tectonics, drifts of up to 10 cm per year;

• Ocean tide loading, with an amplitude of several cm on a daily and sub-daily time scale [28];

• Atmospheric loading, with an amplitude of a couple of cm on annual to sub-diurnal time scales [29];

• Hydrological loading, several mm on a several day time scale [30].
2.3.2 Applications

The main extractions of geodetic VLBI are reference frames, both terrestrial and celestial (TRF and CRF) and Earth orientation. Other applications are, for example, troposphere and ionosphere, and relativity. Reference frames and Earth orientation are discussed in the following.

Reference frames

VLBI is the most accurate technique when defining reference frames, both the Celestial Reference Frame (CRF) and the Terrestrial Reference Frame (TRF), which have their origin at the center of mass of the Earth. Because quasars are located at great distances, they appear to stay in place, as seen by the observer. The observed source positions are used to realize the International Celestial Reference System (ICRS). VLBI is the only technique capable of measuring all the Earth Orientation Parameters (EOPs), and station coordinates. Thus VLBI is used to tie the ICRF to the International Terrestrial Reference System (ITRS), which is the realization of the International Terrestrial Reference Frame (ITRF).

Earth orientation

Earth-related applications are divided into two categories: either the orientation of the structure is treated as a whole, or the motions of its crust are inspected. The causes behind these categories are for example Solar system dynamics, the Earth’s internal processes, or processes of oceanic or atmospheric origin. One of these is the irregular slowing of the Earth’s rotation, which necessitates the introduction of occasional leap seconds in order to keep the Earth’s rotation and atomic time synchronized [12]. Below precession, nutation, polar motion and dUT1 will be discussed.

Precession of the equinox is caused by the motions of two planes: the plane of the Earth’s equator and the ecliptic, the mean plane of the orbit of the Earth-Moon barycenter. The planes are both dynamically involved in the motion of the Earth’s pole [31]. Nutation is caused by the periodic changes in the gravitational forces and the free core oscillations of the Earth [32]. Polar motion is caused by the movement of the rotational axis of the Earth [33]. The polar motion drift is caused by the motions of the Earth’s core and mantle. Isostatic rebound and the re-distribution of water masses also contribute to the wobble. Precession and nutation are depicted in Figure 2.2.

The Earth Rotation Parameters (ERPs), dUT1 and polar motion are usu-
Figure 2.2. Precession and nutation.

ally analyzed with one offset and one time derivative (rate) averaged over one observing session of 24 hours, when obtained from VLBI observations [35]. The accuracy of repeatability of the determination of the ERPs depends on the observing network. For UT1 a long East-West baseline is needed, and for polar motion a long North-South baseline is necessary. For the ERPs the solid Earth tides, the atmosphere, and the oceans cause the largest scale effects.

Because of the importance of the EOPs in general, it is important to understand the accuracy of the VLBI technique. The largest effects are caused by the solid Earth tides and mass redistributions in the atmosphere and in the oceans. The largest earthquakes cause an effect on dUT1 which is less than one microsecond.

Tidally-induced shifts of mass in the solid Earth, oceans, and atmosphere carry angular momenta which must be redistributed in a manner that conserves the total angular momentum. This leads to variations in the orientation and rotation rate of the Earth in the form of modifications to polar motion and UT1. Modeling them is important if sub-centimeter accuracy is to be attained in the interpretation of VLBI measurements [12]. Variations in UT1 caused by solid Earth tides have periods from 5 to 35 days. There are also longer-period contributions but not until a period of 90 days is reached [12]. The dominant effects caused by ocean tides on polar motion and UT1 occur with diurnal, semidiurnal, fortnightly, monthly, and semiannual tidal periods.
**Polar motion**

The Earth’s instantaneous spin axis traces a quasi-circular, quasi-periodic path approximately 20 m in diameter with a period somewhat less than one year, which is known as polar motion [12]. The term polar motion denotes the variation of the geographic poles of the Earth, and is largely of geophysical origin. The motion of the rotation axis of the Earth relative to the crust has three major components, the first of which is a free oscillation with a period of about 435 days called Chandler wobble, first observed by Chandler [34] in 1891, although it was predicted earlier by Euler in 1765.

The two other components arise from seasonal displacements of air and water masses, giving the characteristic annual oscillatory shape of the motion. These internal mass redistributions and angular momentum exchanges between the solid Earth and geophysical fluids (atmosphere, oceans, hydrology, tides, mantle, and core) lead to variations of the Earth rotation rate and time-dependent polar motion [35].

In Figure 2.3 the other ERP, polar motion, from C04 data from 2000 to 2013 is displayed. Polar motion can be described as a wobble motion of the rotation axis of the Earth with the respect to the z-axis of the co-rotating reference frame.

![Figure 2.3. Polar Motion in mas for both Xpol and Ypol from January, 2000 to January, 2013.](image)

The principal period of nutation is 18.6 years and is due to the regression of the nodal line of the orbit of the Moon, which has the same period [32]. The second largest period is 0.5 year. Lunar nodes are depicted in
Figure 2.4. The Earth goes through one precessional cycle in a period of approximately 26 000 years.

![Image of Lunar nodes](image)

**Figure 2.4. Lunar nodes.**

*dUT1*

Sidereal time is related to the observed rotation of the Earth. The measurements of the radio source positions are adjusted for precession, nutation, and so on, and thus depend only on the angular velocity of the Earth and on polar motion [21]. Universal Time (UT) is a time standard based on the rotation of the Earth. The uncorrected (for the displacement of Earth’s geographic pole from its rotational pole) time term is called Universal Time: UT0 when it is not corrected for polar motion and UT1 when it is corrected. UTC follows the International Atomic Time (Temps Atomique International, TAI), but is corrected by a leap second, when the difference with UT1 is more than 0.9 s. The difference UT1-UTC is described by the Earth rotation parameter called *dUT1*.

Universal Time (UT) is described in detail in [36]. *dUT1* is measured rather than calculated, and it is possible to predict it by extrapolation with satisfactory accuracy only for periods of one to two weeks [21]. Predictions are needed for example for calculating satellite orbits. *dUT1* is used to estimate the orientation of the Earth, which is crucial when determining the orbits of satellites. To measure *dUT1*, an East-West baseline is needed. The IVS intensive sessions, which are scheduled especially to measure the *dUT1* parameter, have the following baselines: Wettzell - Kokee, Wettzell - Tsukuba, and Wettzell - Tsukuba - Ny Ålesund.

If $\Delta X$, $\Delta Y$, $\Delta Z$ represent the change in the baseline component in directions X, Y, and Z caused by polar motion, and a time variation *dUT1* corresponds to $\theta_{dUT1}$ radians, the following can be written (equations from
Very Long Baseline Interferometry

\[
\begin{bmatrix}
\Delta X \\
\Delta Y \\
\Delta Z
\end{bmatrix} =
\begin{bmatrix}
0 & -\theta_{dUT1} & -x \\
\theta_{dUT1} & 0 & y \\
x & -y & 0
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

where the square matrix is a three-dimensional rotational matrix valid for small angles of rotation. \(\theta_{dUT1}, x \) and \(y\) are the rotational angles about the \(x, y\) and \(z\) axes. From the matrix we obtain

\[
\begin{align*}
\Delta X &= -\Theta Y - xZ, \\
\Delta Y &= \Theta X + yZ, \\
\Delta Z &= xX - yY
\end{align*}
\] (2.4-2.6)

Equations 2.4-2.6 can be used to determine UT1 and polar motion. In this case a series of sources at periodic intervals needs to be observed, and variation in baseline parameters needs first to be determined. For an East-West baseline \((Z = 0)\) \(\Theta\) can be determined, but the effect of \(x\) and \(y\) cannot be separated. In general all three quantities cannot be measured by a single baseline, since a single direction is specified by two parameters only [21].

Global Navigation Satellite System

Because GNSS satellites orbit the Earth, their observed positions are affected by the change in the rotation of the Earth described with the \(dUT1\) parameter. The American GPS and the Russian GLObal NAvigation Satellite System (GLONASS) are operational, and the European Galileo and the Chinese Compass are in development. GLONASS satellites have the lowest orbital height of the four, 19 130 km, and Galileo the highest, 23 220 km. The orbital period of GLONASS is the shortest, 11 h 16 min, and the orbital period of Galileo the longest, 14 h 5 min. GPS is currently the most utilized satellite navigation system in the world and 8-10 satellites are visible at any point on the ground at any time. It came operational in 1978 and globally available in 1994. The system consists of 32 medium Earth orbit satellites in six orbital planes. GPS uses frequencies 1.57542 GHz (L1 signal) and 1.22760 GHz (L2 signal). GLONASS came fully operational in 1995 with its 24 satellites in three orbital planes. It uses frequencies 1.602 GHz and 1.246 GHz. After funding problems due to the collapse of the Soviet Union, the system has been fully operational again since 2011. The system’s orbit makes it
suitable especially for high latitudes where a GPS signal might be hard to reach. The GLONASS receiver needs to be in range of at least four satellites, three of which will be used to determine the user’s location and the fourth to synchronize clocks of the receiver and the three other satellites. Galileo is planned to be operational in 2014 with its 30 satellites in three orbital planes and Compass by 2020 with 30 satellites in medium Earth orbits and five in geostationary orbits. Galileo uses frequencies 1.164-1.215 GHz, 1.260-1.300 GHz and 1.559-1.592 GHz, and Compass 1.561098 GHz, 1.589742 GHz, 1.20714 GHz and 1.26852 GHz. The accuracy of the user-determined position with a GPS receiver is directly related to the accuracy of the GPS orbit information\(^2\). The position of the satellite in its orbit is slightly affected by the orientation of the Earth. Earth's orientation affects the positional accuracy due to the TRF. Thus, it is highly important to be able to measure the EOPs with the best possible accuracy.

\(^2\)http://www.noaa.gov/orbits/
3. Materials and methods

3.1 Metsähovi Radio Observatory

Metsähovi Radio Observatory has Finland’s only radio telescope that is used for astronomical and geodetic observations. Its diameter is 13.7 m and it has been operational since 1974. The telescope is situated within a radome. The upgrading of the telescope was done during 1992-1994 during which time the radome was replaced with a new one and new surface panels were installed. The surface accuracy of the present telescope is 0.1 mm (Root Mean Square (RMS)), and the antenna speed is 1.2 degrees per second.

3.1.1 Equipment

The receivers at Metsähovi Radio Observatory include those for astronomical VLBI that operate at 22, 43, and 86 GHz, and the geodetic S/X receiver. The Finnish Geodetic Institute (FGI) started geodetic VLBI observations in 2004, and a Mark 5A system was purchased by FGI for the geodetic VLBI sessions in 2006. PC-EVN, where EVN stands for European VLBI Network, developed at Metsähovi Radio Observatory, can be used without disk modules, and is used in parallel with Mark5A in the geodetic VLBI experiments. The PC-EVN is also used for transferring data to the Bonn correlator via Internet after each geodetic session. Mark5B+ was purchased by Metsähovi Radio Observatory in early 2012 to replace the Mark5A and the formatter, which had started to become unsynchronized during geodetic and astronomical VLBI experiments. A NEXPReS computer built of Commercial Off The Shelf (COTS) devices and developed at Metsähovi Radio Observatory will enable e-VLBI measurements and real-time correlation of the results.
A Digital Baseband Converter (DBBC) was ordered to Metsähovi Radio Observatory in late 2011 to replace the aging rack BBCs. The DBBC has two input IFs: IFA and IFB, which both have eight channels to replace the 14 channels of the rack BBCs. The DBBC will be used together with Mark5B+, and the FlexBuff with the FILA10G. The FlexBuff and the FILA10G could be used in the future for the e-transfers. A new Field System computer will be attained, or will be installed within the Mark5B+ internal computer, to enable parallel recording with DBBC + Mark5B+ combo, and BBC + Mark5A combo. If needed, the data can also be recorded with the PC-EVN and the FlexBuff, to simplify the e-transfer. After the DBBC + Mark5B+ system is fully operational and tested, the usage of the BBC + Mark5A will be stopped. VLBI equipment in general will be described in the following sections.

3.1.2 Networks

Metsähovi Radio Observatory has been participating in VLBI experiments since 1991. The networks Metsähovi belongs to are IVS, European VLBI Network (EVN)\(^1\) and Global Millimeter VLBI Array (GMVA)\(^2\). In addi-
\(^1\)http://www.evlbi.org/
\(^2\)http://www.mpiib-hannover.mpg.de/div/vlbi/globalmm/
tion to the European stations, Very Long Baseline Array (VLBA)\textsuperscript{3} stations also participate in GMVA sessions. Metsähovi Radio Observatory has observed in the IVS since the early 2000’s in co-operation with FGI. In the EVN sessions the observations at Metsähovi are done with the 22 GHz receiver, in GMVA sessions with the 86 GHz receiver, and in IVS with the S/X band receiver.

3.2 VLBI equipment

VLBI equipment at a station consists of a radio telescope, receivers for different frequency bands, hydrogen maser(s), backend, formatter, recorders and storage media. The following sections describe the equipment in more detail starting from the radio telescopes, receivers, hydrogen masers, backends and recorders. The equipment of Metsähovi Radio Observatory, the Field System, and e-transfer will also be described.

3.2.1 Radio telescopes

Most VLBI stations have one or two parabolic radio telescopes. However in the present day, if a station has two telescopes they are operated separately. For example, one may be used for astronomical and the other for geodetic observations. Because of the different sizes of the telescopes, their slew speeds are different. Also RMS surface accuracies vary. The requirements for VLBI2010-compatible radio telescopes are mentioned in Chapter 3.3.5. It also should be noted that most of the astronomical observations are single-dish observations, as is the case at Metsähovi Radio Observatory, where they monitor the long term intensity of distant quasars. In the near future more so-called twin telescopes will be built. The most famous of these is the one in Wettzell which is supposed to be functional in April 2013, and has an important role in the IVS [3] and in VLBI2010 [1].

3.2.2 Receivers

In astronomical VLBI a wide range of frequency bands is deployed. For example Metsähovi Radio Observatory has 22, 43 and 86 GHz receivers. In geodetic VLBI a S/X dual receiver is used that needs to be cooled down before usage. The S band corresponds to 2.3 GHz and the X band to 8.3 GHz.

\textsuperscript{3}http://www.vlba.nrao.edu/
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Figure 3.2. The clock difference measurement in 2012 between a hydrogen maser, a GPS clock (in red) and another hydrogen maser (in green).

GHz. The S band is used to remove the effect of the ionosphere from the data. In the near future, wide-band receivers will be deployed in geodesy for VLBI2010. One of the main reasons for this is that the radio spectrum, especially near 2 GHz, is extremely prone to RFI.

3.2.3 Hydrogen masers

A time tag from a hydrogen maser is added to the recorded data at each station in order to facilitate fringe finding at the correlator. The maser oscillation relies on stimulated emission between two hyperfine levels of atomic hydrogen, and has a resonant frequency of 1420.405.751.768 Hz. For example, CHI 75 has a long-term frequency accuracy of about +/-5 x 10^-16 over five years [37] according to specifications. In Figure 3.2 the GPS and hydrogen maser signals are compared to another hydrogen maser. The device for comparing clock systems was designed by the author in 2003 [38]. The precision is 10 ns in 1 s.

3.2.4 Backends

The Baseband Converter (BBC) is used to downconvert the signal from the intermediate frequency distributor to the baseband frequency band.
with a sideband separating the mixer and tuneable local oscillator. The
downconversion produces two outputs, one for the upper sideband and
one for the lower sideband. For geodetic VLBI fourteen BBCs are needed
(eight in the X-band, and six in the S-band), and for astronomical VLBI
eight BBCs are used. The BBCs were mainly built in the 1970's, and are
now being replaced with digital backends. The DBBC ([39] and [6]) is de-
signed at the Max-Planck Institute for Radio Observatory and INAF, and
manufactured by the Hat-Lab s.r.l. RDBE is based on the ROACH board
and has been developed by the National Radio Astronomy Observatory
(NRAO) and MIT Haystack Observatory.

*Digital Baseband Converter*

The DBBC [39] system is based on a flexible architecture, composed of
one or more FPGA boards as computation elements, placed in a mixed
cascaded/parallel structure to guarantee a parallel usage of data input
and a shared parallel output data flow. In a DBBC, a single system unit is
composed of two or four Radio Frequency (RF) / Intermediate Frequency
(IF) inputs. In the case of four inputs, they are in the ranges 0.01-512
MHz, 512-1024 MHz, 1024-1536 MHz, 1536-2048 MHz, with each of them
feeding a 1.024 GHz clock sampler. Then four polarizations, or bands, are
available for a single group of output channel selection. A group of 64
channels is able to handle a shared combination of channels coming from
the four bands, supporting two VLBI Standard Interface (VSI)\(^4\) output
connectors as output [39]. The four IFs (IF1abcd, IF2abcd, IF3abcd and
IF4abcd) can replace sixteen old-type analog BBCs. If two IF inputs are
used, wider bandwidths are enabled (0.01-1024 GHz and 1024-2048 GHz).
In VLBI2010 eight IFs are required at 1024 GHz, as is an input data rate
of 32 Gbps. The FILA10G is the first and last board of the system, which
creates Ethernet packages.

The DBBC stack is described in Figure 3.3. The connection between the
IF signals coming from the VLBI receiver to the DBBC system is realized
by the Conditioning Module (a UNICA3 or UNICA4 board). On the rear
side of the DBBC four separated modules are placed, one for each IF. The
RF inputs are selected by software. The selected signal is then routed
after level adjustment to a set of filters, one from 10 to 512 MHz, the
other from 512 to 1024 MHz. The edge frequencies are defined at -15 dB.
The system bandwidth is from a few MHz up to 2.2 GHz [6].

\(^4\)http://www.vlbi.org/vsi
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An analog-to-digital conversion is performed by a sampler board, ADB1 or ADB2. The ADB1 Board is the analog interface of the DBBC stack and has an analog input of 0-2.2 GHz. It has a sampling clock with a maximum of 1.5 GHz, and its maximum bandwidth in the real mode is 750 MHz, and in the imaginary mode 1.5 GHz. It is able to produce an 8-bit representation of the input analog signal that can be single-ended or differential. The ADB2 board has an input of 0-3.5 GHz, and a sampling clock with a maximum of 2.2 GHz. Its maximum bandwidth in the real mode is 1.1 GHz, and in the imaginary mode 2.2 GHz. Where the ADB1 board has output data of 2 x 8-bit at 1/8 sampling clock frequency, the ADB2 has 4 x 8-bit. ADB2 also has piggy-back support for the FILA10G board. The FILA10G board is used for connection and service. The first board has three functionalities: communication interface, JTAG interface and 1 PPS input. The last board also has three functionalities: two VSI interfaces, digital to analog conversion and 1 PPS output. The DBBC also has an internal PC.

Multiple architectures can take advantage of adopting fully re-configurable FPGA Core Modules, which are autonomous boards populated with an appropriate number of gates, fed by any of the four IFs, and which share the output data bus [39]. The Core Modules are the basic processing units of the DBBC system. Narrow or wide bandwidth channels per module can be assigned, to maintain the maximum number of gates provided by the Core Module. One Core Module can be used to replace four analog BBCs. The Core2 board has a maximum input and output data rate of 32.768 Gbps. Field System support is used to configure the different modules and allow standard settings. Different configurations can be supported to obtain different functionalities, such as the SSB down converter, wide band parallel FIR, poly-phase Finite Impulse Response (FIR) / Fast Fourier Transformation (FFT), among others.

The Metsähovi DBBC has two IFs, which can be used for both geodetic and astronomical VLBI:

- geo: S- and X-bands

- astro: Right Circular Polarization (RCP) and Left Circular Polarization (LCP)

The DBBC has, for example, the following observing modes: the Digital
Down Converter (DDC), the Polyphase Filter Bank (PFB), and a 16000 channel spectrometer SPECTRA. In DDC the input is down-converted into tunable baseband channels. PFB performs a conversion to baseband and is non-tunable with 32 MHz fixed bands. After the configuration file has been run, the suitable client program should be run to enable the use of the correct observing mode.

**Roach Digital Backend**

Another digital backend, based on the ROACH board, has been developed by the National Radio Astronomy Observatory (NRAO) and MIT Haystack Observatory. The Roach Digital Backend (RDBE) has both PFB and DDC properties. The initial configuration outputs have sixteen 32 MHz channels, comprised of half the channels from the PFB processing of the two IF inputs, for use in the VLBI2010 geodetic system [1] and in the VLBA sensitivity upgrade project. The output rate is 2x10^9 bits/second (1x10^9 bits/sec = 1 Gbps) over a 10 Giga-bit Ethernet (GE) connection to the Mark 5C with the data written in Mark 5B format on disk [40].

### 3.2.5 FILA10G

The FILA10G is a 10G optical fibre ethernet board, which is either placed inside the DBBC or can be used as a stand alone unit, as is done in Metsähovi. FILA10G has a triangle connection: High Speed Interface (HSI), VSI and 10G link. It has two independent 10 GE User Datagram Protocol (UDP) ports, which can be used bi-directionally, to send and receive data. Data rates which can be used are 1 - 2 - 4 - 8 Gbps for each port. Either Mark5B or VLBI Data Interchange Format (VDIF), the simplest form, can be selected. The standalone version has four VSI connectors and communication is usually performed through a serial port (ethernet can also be used). To achieve the data rate required for VLBI2010, two FILA10Gs are needed (32 Gbps).

The standalone FILA10G is connected to the DBBC VSI outputs, which are the inputs of the FILA10G. The copies of these inputs are placed in two outputs, which can be connected to, for example, Mark5B+ and PC-EVN untouched. The two 10G outputs are realized with XFP transmitters, and the data that has been transformed into ethernet-packets are sent to two different Internet Protocol (IP) addresses. The unit also has a serial connection, ethernet connection and a USB JTAG port which can be used to connect the FILA10G to the DBBC.
Figure 3.3. DBBC stack (modified from [6]), IF stands for Intermediate Frequency, AD for analog-to-digital, VSI for VLBI Standard Interface and CaT is a timing board, and First and Last (FILA), IF, Analog-to-Digital (AD), VSI.
3.2.6 Formatter

The data from the BBCs/DBBC/RDBE is low-pass filtered and time sampled with one- or two-bit resolution and formatted into data frames with accurate time stamps by the formatter. After the formatting and time stamping the data are recorded with a Data Acquiring System, DAS. The most commonly used DASs are described in the following section.

3.2.7 Recorders

At the moment the most commonly used DAS by the VLBI community is the Mark5 [41]. Another system used at European VLBI stations is the PC-EVN [42]. Two of the next generation DASs are the Mark6 and the FlexBuff. These recorders will be discussed in the following subsections; however, not all possible available recorders (for example the Japanese DAS developed by NICT and XCube) will be covered.

Mark5A/B/B+/C and Mark6

The Mark5 systems [41] are designed by the MIT Haystack Observatory, and manufactured by the Conduant corporation. The systems rely on using disk modules for data storage. The follow-up to the Mark5 is the Mark6 also designed by the MIT Haystack Observatory. The Mark6 will use four 10GE ports, and will write to four eight-disk modules with SATA disks. In the future the use of six or eight eight-disk modules will be enabled. The Mark6 will use only six commands, of which two are only to be used by NRAO.

PC-EVN

The PC-EVN [42] was developed at Metsähovi Radio Observatory in the early 2000’s. The basic concept of PC-EVN is that it is assembled from Commercial Off The Shelf (COTS) components and does not require the use of disk modules; the data are stored locally and can be transferred via Internet. The PC-EVN is used in parallel with the Mark5 system in Metsähovi Radio Observatory, and data are transferred to the Bonn correlator after each successful geodetic VLBI experiment.

5http://www.conduant.com/products/mark5vlbi.html
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**NEXPReS DAS**

In the EU-funded Novel EXplorations Pushing Robust e-VLBI Services (NEXPReS) project\(^6\) Metsähovi Radio Observatory is developing a DAS called FlexBuff, capable of multi-Gbps recording and storage. FlexBuff records the UDP packet stream from, for example, DBBC/ FILA10G, Roach or iBob. It allows simultaneous read access for correlation and a data rate of more than 30 Gbps is achieved.

### 3.2.8 Field System

The commands during a VLBI session are given through the Field System (FS)\(^7\), which combines the use of the VLBI equipment. The Field System will also, for example, execute commands for the DBBC. When using these one can control the DBBC through the Field System.

### 3.2.9 e-transfer

The European stations are making an effort to transfer VLBI data electronically via Internet (e-transfer). Most of the geodetic VLBI sessions are transferred via e-transfer. When the data recording and storage is performed with the PC-EVN (and the FlexBuff in the near future), no disk modules are needed for e-transfer. At the moment Metsähovi is transferring geodetic VLBI data via the Internet only to the Bonn correlator, but in the future the Haystack correlator will be included. Astronomical data has been transferred to the JIVE correlator a few times per year.

### 3.3 International VLBI Service for geodesy and astrometry

The International VLBI Service for geodesy and astrometry (IVS [3]) is an international collaboration of organizations which operate or support VLBI components. Metsähovi Radio Observatory has been an official network station of the IVS since 2012. IVS components consist of a coordinating center, network stations, operation centers, correlators, data centers, analysis centers and technology development centers. The IVS components are displayed on the map in Figure 3.5 (Metsähovi Radio Observatory belongs to IVS, but is not yet on the map).

\(^6\)http://www.nexpres.eu
\(^7\)http://www.naic.edu/~astro/avolbi/fsdoc/fsindex-full.html
3.3.1 IVS weekly sessions

IVS observes both 1-hour intensive sessions and 24-hour sessions weekly. The intensive sessions are marked with INT (INT1, INT2 and INT3), and 24-hours sessions with R (R1 and R4, where 1 stands for the session always taking place on a Monday, and 4 the session taking place on a Thursday). Both types of sessions will be described in the following two subsections.

INT1, INT2 and INT3

The IVS intensive sessions are dedicated to providing UT1 results. The intensive sessions are measured daily, and they have a duration of one hour. INT1 sessions are scheduled from Mondays to Fridays, INT2 sessions from Saturdays to Sundays, and INT3s are measured on Monday mornings. Two (INT1 and INT2) to three (INT3) radio telescopes participate in the intensive sessions. The baselines for the sessions are listed below:

**INT1:** Wettzell - Kokee
**INT2:** Wettzell - Tsukuba
**INT3:** Wettzell - Tsukuba - Ny Ålesund

IVS intensive, INT1 (Wettzell - Kokee) and INT2 (Wettzell - Tsukuba) / INT3 (Wettzell - Tsukuba - Ny Ålesund), baselines are displayed in Figure 3.4. The products are available in one weeks time from observation\(^8\).

The correlators for the sessions are:

**INT1:** Bonn
**INT2:** Geospatial Information authority of Japan (GSI)
**INT3:** Washington

R1 and R4

The purpose of the 24-hour sessions is to produce EOP results twice a week. The two 24-hour sessions are measured on Mondays (R1) and on Thursdays (R4). Eight stations participate in the experiments.

The "R" stands for rapid turnaround because the stations, correlators, and analysts have a commitment to make the time delay from the end of recording to results as short as possible. The goal for the time delay is maximum 15 days, but in practise it is 1-4 weeks. The R1s are correlated at the Bonn correlator, and the R4s are correlated at the Washington correlator.

\(^8\)ftp://ivscc.gsfc.nasa.gov/pub/misc/15wmevga/source/IVS-WG2.pdf
3.3.2 Other IVS sessions

IVS has several regional sessions, such as the EURO described in the following subsection, IVS-OHIG (Antarctica), AUSTRAL (Australia and New Zealand), APSG and JADE (both Asia and Pacific). Other experiments include, for example, CRF and 20 station EOP/TRF/CRF devoted sessions.

EURO and T2

The purpose of the EURO sessions is to determine the station coordinates and their evolution in the European geodetic VLBI network. The purpose of the IVS-T2 sessions is to monitor the TRF via bi-monthly sessions. All geodetic stations participate in at least two T2 sessions each year. Metsähovi Radio Observatory and FGI participate in both types of these sessions.

CONT campaigns

The CONT campaigns are campaigns of continuous VLBI sessions. The most recent CONT campaign was CONT11, which was observed in the second half of September 2011. The CONT campaigns have been observed at irregular intervals since 1994. The most recent CONT campaigns were observed at roughly three-year intervals as CONT02 (October 2002), CONT05 (September 2005), and CONT08 (August 2008).
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R&D sessions
The Research and Development (R&D) sessions are scheduled about ten times per year. The sessions are operated, for example, to test different source distributions in the sky to improve results, or to test different networks of radio telescopes. About eight stations participate in the R&D sessions.

3.3.3 Other sessions
Metsähovi Radio Observatory has also participated in the Fennoscandian - Japanese Ultra-rapid dUT1 experiments with Onsala Space Observatory, and the Kashima and Tsukuba stations in Japan. The scientific purpose of these sessions is to obtain the Earth rotation parameter dUT1 via near real-time.

3.3.4 Analysis software
The core task of the post-correlation software is to take the set of phase samples $\phi(\omega_i, t_j)$ from the various frequency channels $\omega_i$ and times $t_j$, and to fit the set of $\phi(\omega_i, t_j)$ with three parameters: the phase $\omega_0$, the group delay $\tau_{gd}$, and the phase rate $\tau_{pd}$. To accomplish this, the set of $e^{i\phi(\omega_i, t_j)}$ are first Fourier transformed from the frequency and time domain to the delay, and delay rate domain respectively [12]. The phase-derived observables are determined for phase $\phi$ and circular frequency $\omega$ from a bilinear least-squares fit to the measured phases $\phi(\omega, t)$ (equations from [12]):

$$\phi(\omega, t) = \phi_0(\omega_0, t_0) + \delta \phi / \delta \omega (\omega - \omega_0) + \delta \phi / \delta t (t - t_0) \quad (3.1)$$

where the phase, group delay, and phase rate are respectively defined as

$$\tau_{pd} = \phi_0 / \omega, \quad (3.2)$$

$$\tau_{gd} = \delta \phi / \delta \omega, \quad (3.3)$$

$$\tau_{pd} = \delta \phi / \delta t \quad (3.4)$$

Formal uncertainties of each observable are also produced. When data at two frequency bands are present (e.g., S and X bands), charged particle (ionospheric) effects are removed by applying a simple model of dispersion, and combined (S/X) observables are formed. Problems with resolving
2π ambiguities in the signal phase over large distances usually preclude the direct use of the phase delay observable $\tau_{pd}$ [12].

There are several analysis software packages used in geodetic VLBI. The most commonly used is the Calc/Solve [5] software. Other software packages are, for example, Occam [43] and SteeleBreeze9. The newer software packages include Vienna VLBI Software [4], C5++ [44] and nuSolve [45].

Calc/Solve
Calc/Solve has been developed at the Goddard Space Flight Center (GSFC) since the mid 1970's, and is the most commonly used software by the geodetic VLBI community. It consists of 109 programs and 3680 modules with 1.02 million lines of source code written mainly in Fortran-95. The user can estimate, for example, station positions and velocities, source coordinates and EOPs with Calc/Solve. The software can also be used to evaluate the performance of the stations, and to maintain the databases of the VLBI experiments. From these databases the NGS cards10 used, for example by VieVS, are created with Calc/Solve.

Solve can be used to resolve the group and phase delay ambiguities, to adjust the parameters, and to visualize the observables and residuals. Solve has both interactive and batch modes which have the following operational modes:

1. First analysis right after correlation of an experiment;
2. Re-analysis of an individual experiment;
3. Analysis of several sessions independently;
4. Analysis of several sessions combined;
5. Special analysis of observations with user programs.

VieVS
All the data analyzed in this thesis were processed with the Vienna VLBI Software (VieVS [4]) developed at the Technical University of Vienna. VieVS has its origins in OCCAM and is a Matlab-based software, which can be used in both batch and interactive modes. The interactive mode uses Graphical User Interfaces (GUIs). Matlab was chosen because uni-

9http://steelbreeze.sourceforge.net
10http://lacerta.gsfc.nasa.gov/mk5/help/dbngs_format.txt
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Universities have licenses for it, and students and personnel all over the world are experts in Matlab coding. Other advantages of Matlab include relative ease of installing your own add-ons to the VieVS software, and GUIs that make using the software intuitive.

The main differences with OCCAM is the use of a functional model in least-squares adjustment with piecewise linear offsets at integer hours, and the use of non-rotating origin right from the beginning (no equinox-based transformation - Resolution IAU 2000) [46].

System requirements for VieVS are [46]:

- Matlab 7.6 (R2008a) or later (running on older Matlab version is possible but without using GUIs)

- about 6.4 GB of disk space (including all data files; source code has less than 10 MB)

The majority of disc space required by VieVS is taken up by data files called NGS cards. The NGS cards, the mapping functions, the atmospheric files, and the EOP files need to be downloaded regularly. The VieVS source code and data files can be downloaded using ssh/sftp from the VieVS server: vievs.hg.tuwien.ac.at

The NGS version 4 cards contain the observed delay, and the delay rate with ambiguities already solved, the ionospheric delay and the delay rate. Other measurement results such as the the quality code of the observation, the cable length (geodetic VLBI observations require calibration of the phase change due to temperature variations along the IF cable and the 5 MHz reference signal), temperature and pressure at a station are also recorded onto the version 4 files.

Files used and created by different parts of VieVS are described in [46]. The user can create her own parameter files and process lists to enable quick analysis of the data. In a parameter file the user can define the parameterization required for the analysis, e.g. the user can choose from different EOP files, mapping functions, TRFs (ITRF2005, VTRF2008 or VTRF2008), CRFs (ICRF or ICRF2) et cetera. The OPT-file created by the user contains information about clock breaks, and stations, baselines and sources to be excluded. The outlier files are created in the VIE_LSM, and removed in the VIE_INIT. To create an outlier file the user needs to run VieVS twice; in the first run VieVS saves the information about
the outliers (baseline, and MJD) to the outlier file, and in the second run VieVS in the VIE_INIT uses the file to remove the outliers.

**Ambiguity resolution in different softwares**

The following two sections describe the ambiguity resolution in two geodetic VLBI softwares, Calc/Solve and C5++. Ambiguity resolution and ionospheric correction need to be implemented in VieVS to make its use independent of Calc/Solve.

**Ambiguity resolution algorithm in Solve**

In the Solve software the group delay ambiguity resolution algorithm has five steps (descriptions and Equation 3.5 from [47]):

- Calculation of an ionosphere-free linear combination of group delay observables. Ionosphere contribution is about 0.2-2.0 ns for X band, and 3-30 ns for S band.

\[
\Delta \tau_x = \tau_0^x + (\tau_0^x - \tau_0^s) \cdot f_2^s / (f_2^x - f_2^s)
\]

The difference \((\tau_0^x - \tau_0^s)\) may be contaminated with both S and X band ambiguities, which may lead to jumps in the ionosphere-free combination of group delay observables.

- Redistribution of differences between stations. A correction of estimates should be found for differences in order to keep triangles of ionosphere contributions and thus ionosphere-free group delay observables closed.

- Obtaining ionosphere-free observables. The ionosphere free observables do not have jumps due to different ambiguities at X and S bands, but may have jumps due to the same ambiguities for both bands.

- Resolving group delay ambiguity for the observations of one baseline. The entire set of observations is divided into subsets of the observations for a single one baseline. All observed-calculated (o-c) delay rates are scanned, and those below a threshold value are used to calculate a linear trend. The points which exceed the threshold will be treated again with a doubled threshold value. A linear and a quadratic term will be subtracted from the group delay observables. The set of observations of the baseline is divided into segments. The segment that contains a maximal number of points will be found. An average of the o-c of the
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group delay for the segment gives out the first approximation for the clock shift for the current baseline. The ambiguity jumps are set to zero for all the points of this segment.

- Redistribution of permanent ambiguities between station clocks. A clock function needs to be found for all but one station. The clock shift for all baselines has an ambiguity which is a multiple of the group ambiguity spacing. The algorithm used is similar to the one used for the redistribution of fiducial differences between stations. The ambiguity jumps for all observations of all baselines for permanent ambiguity of a clock shift of the baseline are corrected.

**Ambiguity resolution in C5++**

In C5++ the ambiguities are resolved automatically for both single [49] and multiple baselines [48]. The C5++ implementation of the ambiguity estimation algorithm for a single baseline introduces X- and S-band delays as independent observations. Thus, the integer nature of the ambiguities does not change, but the ambiguity shifting based on the residual must be split according to the spacing of each band [49]. Shifting the ambiguities and simplified geodetic adjustment is iterated as long as the residuals do not exceed the corresponding ambiguity spacings. This approach will work properly only if the ionosphere delay does not exceed the ambiguity spacing defined by the X/S band set-up.

In order to estimate the ambiguities the following function model can be used:

\[
\tau_x(t) - \tau_{th}(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 
\]

\[
\tau_s(t) - \tau_{th}(t) = b_0 + a_1(t - t_0) + a_2(t - t_0)^2 
\]

where \(\tau_x(t)\) and \(\tau_s(t)\) denote the measured X- and S-band delays. The difference between the theoretical delay \(\tau_{th}(t)\) and the measured delay is assumed to be modeled properly by setting up a polynomial for the clock function, represented by a quadratic polynomial with the clock function coefficients \(a_i\). Equations 3.6 and 3.7 share the same unknowns except the constant clock offset (\(a_0\) and respectively \(b_0\)) which is assumed to be different for each band due to ionosphere delays [49]. Once all ambiguities have been fixed, X- and S-band data can be combined and an ionosphere
correction for each observation can be determined.

The algorithm for multiple baseline uses the following equations [48]:

$$\tau_x = \tau_{th} + a_{0,i} + a_{1,i}(\tau - \tau_0) + a_{2,i}(\tau - \tau_0)^2 - [a_{0,j} + a_{1,j}(\tau - \tau_0) + a_{2,j}(\tau - \tau_0)^2]$$  (3.8)

$$\tau_s = \tau_{th} + b_{0,i} + a_{1,i}(\tau - \tau_0) + a_{2,i}(\tau - \tau_0)^2 - [b_{0,j} + a_{1,j}(\tau - \tau_0) + a_{2,j}(\tau - \tau_0)^2]$$  (3.9)

The coefficients $a_0$, $a_1$ and $a_2$ represent the quadratic station clock model ($b_0$ is an offset with the respect to $a_0$ due to ionosphere delays) and $\tau_{th}$ denotes the a priori delay which should contain a basic atmosphere propagation model with an accuracy better than 25\% of the smallest ambiguity spacing [48].

### 3.3.5 VLBI2010

The VLBI2010 requirements for a new generation of VLBI systems from antennas to analysis set by the working group 3 (WG3), and given in the final report of WG3 [1], are:

1. 1 mm measurement accuracy on global baselines,
2. continuous measurements for time series of station positions and EOPs,
3. turnaround time to initial geodetic results of less than 24 hours.

To achieve the 1 mm goal, there are certain strategies which can be taken into account [1]:

1. reduce the random component of the delay-observable error, i.e., the per-observation measurement error, the stochastic properties of the clocks, and the unmodeled variations in the atmosphere;
2. reduce systematic errors;
3. increase the number of antennas and improve their geographic distribution;
4. reduce susceptibility to external radio-frequency interference;
5. increase observation density, i.e. the number of observations per unit time;
6. develop new observing strategies.
The WG3 recommends that the new VLBI2010 observing systems consist of small 10-12 m fast moving antennas, which will be automated and manufactured at low cost. Wide-range receivers will be used, to observe at 1 - 14 GHz to be compatible with old S and X receivers, but allow more flexibility to avoid Radio Frequency Interference (RFI) and more bandwidth to improve delay measurement precision [1]. Sensitivity requirement for a VLBI2010 antenna is described with System Equivalent Flux Density (SEFD), and has the value of 2500 Janskys [50]. Also the use of old larger antennas, which are needed for the CRF measurements, will continue. The data will be transferred with high-speed networks (a data rate of 32 Gbps) and high data rate disk systems. To obtain TRF, CRF and EOP with a reduced latency the data analysis needs to be automated. New software correlator possibilities will need to be examined.

The WG3 has been divided into seven sub-groups, which have different tasks, and are listed below:

1. observing strategies;
2. RF/IF, frequency and time;
3. backend systems;
4. data acquisition and transport;
5. correlation and fringe-finding;
6. data analysis;
7. data archiving and management.

Recommendations given by the seven sub-groups for a next generation system are:

1. **antenna**  10 - 12 m dish, 60% efficiency, >5 degrees/sec slew;
2. **feed** dual polarization; low cross-polarization leakage;
3. **front end**  1 GHz to 14 GHz continuous RF coverage; Tsys  45K;
4. **backend** digitize signals as early as possible after receiver; channelize into several frequency segments selected from front-end bandwidth, totaling 4 to 8 GHz;
5. **calibration systems** upgraded phase and cable calibration systems;
6. **data rate**  2 - 4 Gbps initially, expanding to 8 - 16 Gbps, potentially to
32 Gbps;
7. **frequency standard** H-maser;
8. **network design** 20 - 40 antennas, globally distributed, co-located with other space-geodetic techniques, including sufficiently capable existing geodetic VLBI antennas;
9. **data transport** mixture of disk-based recording and high-speed network transfer;
10. **correlation** near real time, perhaps distributed among a network of processors;
11. **products** near real time automated generation of rapid response products, later complete analysis;
12. **data archiving** data may be retrieved from an archive on any timescale.

Of these recommendations, 4-7 and 9 are already deployed at Metsähovi Radio Observatory. Recommendations 4, 6 and 11 are directly related to the outcome of this thesis due to the firmware written for the FILA10G board of the DBBC (4 and 6) and the automated analysis with VieVS (11). The first three recommendations will be taken into account when a new VLBI2010-compatible antenna will be built at Metsähovi in 2017 by the FGI.

### 3.4 Geophysical models

Geophysical models used in geodetic VLBI analysis are given in IERS Conventions, currently in IERS Conv. 2010 [57]. Commonly used geophysical models are described below. Purposes for each model will be given. Geodetic parameters are estimated with least-squares adjustment. TRF and CRF coordinates, EOPs, Zenith Wet Delay (ZWD) and troposphere North and East gradients are estimated with piece-wise linear offsets. Clock parameters are estimated with piecewise linear offsets and quadratic polynomial coefficients. Offsets are constrained to zero, for example in case of dUT1, by 0.0001 ms/day. The constraints are necessary to avoid singularity of the normal equation matrix [51]. So-called station corrections include solid Earth tides, tidal ocean loading, atmospheric tidal loading, atmospheric non-tidal loading, solid Earth pole tide and ocean pole tide. These effects, their causes and sizes are given in Table 3.1. In
addition to these, clock and EOP modeling, ionospheric delay, neutral atmosphere and mapping functions will also be described in the following subsections.

<table>
<thead>
<tr>
<th>effect</th>
<th>cause</th>
<th>magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Earth tides</td>
<td>The Moon and Sun</td>
<td>40 cm</td>
</tr>
<tr>
<td>Tidal ocean loading</td>
<td>The Moon and Sun</td>
<td>10 cm</td>
</tr>
<tr>
<td>Non-tidal ocean loading</td>
<td>Changes in water mass, ice mass etc</td>
<td>20 mm</td>
</tr>
<tr>
<td>Atmospheric tidal loading</td>
<td>Diurnal heating of the atmosphere</td>
<td>several mm</td>
</tr>
<tr>
<td>Non-tidal atmospheric loading</td>
<td>Pressure changes due to air mass movements</td>
<td>25 mm</td>
</tr>
<tr>
<td>Solid Earth pole tide</td>
<td>Variation in the centrifugal potential</td>
<td>several mm</td>
</tr>
<tr>
<td>Ocean pole tide</td>
<td>Centrifugal effect of polar motion</td>
<td>a few cm</td>
</tr>
</tbody>
</table>

Table 3.1. Effects causing station corrections in geodetic VLBI analysis.

In Table 3.2 some example values [52] and [53] for some of the loading effects for Wettzell and Kokee Park, which are the stations participating in IVS INT1 sessions, are listed. Because Kokee Park is a coastal site with high humidity, ocean loading effects are dominating and larger than in Wettzell, which is an inland site. In Wettzell ocean loading and atmospheric pressure loading (non-tidal atmospheric loading) values are comparable to each other, -6 mm to 6 mm (peak-to-peak), and 4.9 mm in vertical, while in the case of Kokee the values are not comparable to each other; -25 mm to 20 mm, and 0.9 mm. The effect caused by solid Earth pole tide is a little larger in Wettzell than in Kokee, but the values for the stations are comparable to each other.

3.4.1 Clocks

In geodetic VLBI analysis a reference clock for an entire observing network of a session is chosen. Clocks of remaining stations show a constant difference, called clock offset, and a linear clock trend, or even a higher rate of change relative to the reference clock. Usually in the analysis of intensive sessions, only piece-wise linear offsets [cm] of clock parameters are estimated. In the analysis of the 24-hour sessions quadratic polyno-
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<table>
<thead>
<tr>
<th>effect</th>
<th>Wettzell / mm</th>
<th>Kokee Park / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Earth pole tide</td>
<td>-8 to +7 (peak-to-peak)</td>
<td>-5 to +6</td>
</tr>
<tr>
<td>Tidal ocean loading</td>
<td>-6 to +6</td>
<td>-25 to +20</td>
</tr>
<tr>
<td>Ocean pole tide</td>
<td>-0.7 to +0.5</td>
<td>-3 to +3</td>
</tr>
<tr>
<td>Atmospheric pressure loading</td>
<td>4.9 (vertical),</td>
<td>0.5 (vertical),</td>
</tr>
<tr>
<td></td>
<td>0.9 (horizontal)</td>
<td>0.2 (horizontal)</td>
</tr>
<tr>
<td>ZWD</td>
<td>0.51 mm</td>
<td>-0.11 mm</td>
</tr>
<tr>
<td></td>
<td>(yearly trend)</td>
<td>(yearly trend)</td>
</tr>
</tbody>
</table>

Table 3.2. Example values of loading effects in Wettzell and Kokee Park, from [52] (annual peak-to-peak values), except atmospheric pressure loading from [53] and ZWD [54].

Because station clocks are not perfectly synchronized, there are offsets and drifts between time tags which directly appear as polynomial systematics in residuals. For example, if there is an offset in a clock, there will also be an offset in observations. In order to model clock delay errors the following formulas are defined. In VieVS in the first least-squares adjustment polynomial coefficients of the clocks are estimated with [55]:

$$\Delta \tau_{poly}^{cl}(t) = c_0 + c_1(t - t_0) + c_2(t - t_0)^2$$  \hspace{1cm} (3.10)

In the second adjustment a continuous piece-wise linear offset function is used:

$$\Delta \tau_{cpwlo}^{cl}(t) = x_1 + \frac{t - t_1}{t_2 - t_1}(x_2 - x_1)$$  \hspace{1cm} (3.11)

where $t$ is the epoch of the observation. $\Delta \tau_{poly}^{cl}(t)$ denotes the clock delay error at the observation epoch $t$ represented by the quadratic polynomial. $\Delta \tau_{cpwlo}^{cl}(t)$ denotes the clock delay error at the observation epoch $t$. $t_0$ denotes the first clock estimation epoch at the first integer or fractions of UTC hours before the beginning of the session (epoch of the first continuous piece-wise linear offset clock estimate). $c_i$ are the polynomial coefficients (unknowns) of a clock. $x_1$ and $x_2$ are the continuous piece-wise linear offsets of clocks (unknowns) at integer estimation epochs $t_1$ and $t_2$.

Total clock error at $t$ is:

$$\Delta \tau_{c}^{cl}(t) = \Delta \tau_{poly}^{cl}(t) + \Delta \tau_{cpwlo}^{cl}(t)$$  \hspace{1cm} (3.12)

In software the clock constraint can be given as a standard deviation,
or as a variance. For example, in VieVS, the clock constraint for 24 h sessions, in default configuration, is given as a variance, 0.5 ps$^2$, and for Solve the clock constraint is given as a standard deviation, 50 fs. If the clock estimation interval is 60 min, i.e. there is a variance of 1800 ps$^2$ after one hour, then this corresponds to a standard deviation of 42 ps, and is the standard deviation used for the observation equation in VieVS [46].

3.4.2 Reference frames

International Terrestrial Reference Frame (ITRF) is the basis for the determination of the orientation of the Earth in space. ITRF has its origin in the centre of mass of the Earth, and it has its x- and y-axis in the equatorial plane, with the x-axis intersecting the Greenwich meridian. The z-axis is the mean Earth rotation axis.

ITRF2008 is based on reprocessed solutions of the four space geodetic techniques: VLBI, SLR, GPS and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), spanning 29, 26, 12.5 and 16 years of observations, respectively. The input data used in its elaboration are time series (weekly from satellite techniques and 24-h session-wise from VLBI) of station positions and daily Earth Orientation Parameters (EOPs) [56]. SLR gives TRF its origin, and scale is attained from both SLR and VLBI observations. Origin and scale are realized according to the standards applied for ITRF computation [57].

The ITRF2008 is composed of 934 stations located at 580 sites, with an uneven distribution between the Northern (463 sites) and the Southern hemisphere (117 sites). There are in total 105 co-location sites; 91 of these have local ties available for the ITRF2008 combination. The ITRF2008 origin is defined in such a way that there are zero translation parameters at epoch 2005.0, and zero translation rates with respect to the International Laser Ranging System SLR time series. The scale of the ITRF2008 is defined in such a way that there is a zero scale factor at epoch 2005.0, and a zero scale rate with respect to the mean scale and scale rate of VLBI and SLR time series. The ITRF2008 orientation is defined in such a way that there are zero rotation parameters at epoch 2005.0, and zero rotation rates between ITRF2008 and ITRF2005. [57].

The ITRF2008 orientation at epoch 2005.0, and its rate are aligned to the ITRF2005 using 179 stations. An estimate of the origin components from ITRF2008 to ITRF2005 indicates differences at epoch 2005.0, which are: -0.5, -0.9 and -4.7 mm along X, Y and Z-axis. The translation rate
differences between the two frames are zero for Y and Z, while an X-
translation rate of 0.3 mm/year exists. The estimated formal errors of
these parameters are 0.2 mm and 0.2 mm/yr [56].

VLBI is the only technique capable of observing extragalactic objects, and
thus, the only technique that can determine all EOPs. The scale of the
reference frame is determined with high accuracy. However, the stations
are not optimally distributed on the surface of the Earth, which leads to
somewhat poor accuracy of EOPs.

The transformation between the ITRF and International Celestial Ref-
ence Frame (ICRF) is performed by the means of EOPs, by determining
the movement of the Earth rotation axis in the celestial frame (precession
and nutation), rotation of the Earth relative to its rotation axis (UT1),
and movement of the Earth rotation axis in the terrestrial frame (polar
motion).

Origin and scale of ICRF are realized according to the standards applied
for ITRF computation given in IERS Conventions. The origin of ICRF is
located in the barycentre of the solar system, two of its axes, $e_1$ and $e_2$, lie
within the plane of the mean celestial equator of epoch J2000.0. The $e_1$
axis is directed to the point of the Vernal equinox. The third axis, $e_3$, is the
mean Earth rotation axis. Only sources with positions of high accuracy
are used for the determining of the axis.

Reference frames can be used for, for example, car, ship and aeroplane
navigation, land survey by GPS, mapping, determination of plate tecton-
ics and crustal deformation, sea level change, and post-glacial uplift.

When analyzing geodetic VLBI data, ITRF2008 [56] or VTRF2008 [58]
is usually used as the TRF to obtain site and velocity information, and
ICRF2 [59] as the CRF to obtain the source position information. The
ICRF2 is found to have a source position uncertainties of only 40 μas, and
an axis stability of 10 μas [60]. The IERS EOPs provide the permanent
tie of the ICRF to the ITRF. They describe the orientation of the Celestial
Intermediate Pole in the terrestrial system and in the celestial system
(polar coordinates x and y, and celestial pole offsets $d\phi$, $de$) and the ori-
entation of the Earth around this axis (dUT1), as a function of time. This
tie has the accuracies of 0.2 mas for polar motion, 10 μs for UT1, and 50
μas for precession and nutation [61]. CRF results obtained from global
VLBI solutions depend on the tie to the ITRF. Several problems affect
the source position catalog; dependence on the ITRF datum, dependence
on the set of reference stations used, and dependence on the modeling of
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non-linear station motion [60]. JPL ephemerides is aligned to the ICRS with an accuracy of better than 1 mas [57].

In the analysis of dUT1, all station coordinates, which are available in the selected TRF, are fixed. If they are not fixed, no net translation, and no net rotation condition equations are applied on all stations which are available in the selected TRF. A datum definition can be performed by using the no net rotation condition.

3.4.3 Ephemerides

In 1995 Hartmann and Wenzel [62] published a catalogue, the HW95 tidal potential catalogue, of fully normalized potential coefficients, which contained 12935 waves, including 1483 waves due to the direct planetary effects due to the Moon, the Sun and the planets Venus, Jupiter, Mars, Mercury and Saturn. The catalogue is based on the DE200 numerical ephemerides of the planets and the Moon between the years 1850 and 2150.

The relative magnitude of the lunar and solar tide-raising forces can be understood with the following formula [63]:

\[
\frac{a_L}{a_S} = \frac{M_{\text{Moon}}}{M_{\text{Sun}}} \left( \frac{R_{\text{Sun}}}{R_{\text{Moon}}} \right)^3 \approx 2.2
\]

where \(a_L\) and \(a_S\) are lunar and solar forces, \(M_{\text{Moon}}\) and \(M_{\text{Sun}}\) the lunar and solar masses, and \(R_{\text{Sun}}\) and \(R_{\text{Moon}}\) are the solar and lunar radius.

The positions of the Sun and the biggest planets are currently usually taken from the ephemerides in JPL 421 [64].

3.4.4 EOP models and a priori files

The EOPs consist of nutation and precession, which are caused by periodic and long-term motion of the spin axis relative to CRF; polar motion, which describes the motion of the geographic pole relative to the spin axis; and dUT1, which describes the non-uniform daily rotation of the Earth.

Variations of dUT1 consist primarily of a linear trend. Tidally forced variations can be expressed by poly-harmonic functions [65]

\[
dUT1(t) = \sum_{i=1}^{n} u_i^c \cos\phi_i(t) + u_i^s \sin\phi_i(t)
\]

where \(t\) denotes the epoch of every originally parameterized hourly dUT1 and \(n\) is the number of tidal terms in the model. \(\phi_i\) are the corresponding angular momentums for \(i^{th}\) tide.
\[ \varphi = a_i \cdot l + b_i \cdot l' + c_i \cdot F + d_i \cdot \Omega + f_i \cdot D + (\Theta + \pi) \quad (3.15) \]

The fundamental arguments \( l, l', F, D \) and \( \Omega \) represent the mean anomaly of the Moon and the Sun, the argument of latitude of the Moon, the elongation of the Moon from the Sun, and the longitude of the ascending lunar node. The resulting amplitudes of the sine- and cosine-component of the tidally forced dUT1 are given by \( u_c \) and \( u_s \).

The dominating part of the sub-daily variations is due to the ocean tides where 90\% of the measured tidal dUT1 variations are explained by a tidal ERP model based on a theoretical ocean tidal model [67]. Small variations in dUT1 could be forced by diurnal and semi-diurnal atmospheric effects as this influence is up to two orders of magnitude below the oceanic impact [68].

Polar motion is affected by mass redistributions, tidal variations and angular momentum exchanges between the solid Earth and geophysical fluids. The tidally-induced diurnal and semi-diurnal variations can be modeled by polyharmonic functions [69]

\[
dx_p(t) = \sum_{i=1}^{n} -p^c_i \cos \varphi_i + p^s_i \sin \varphi_i \\
dy_p(t) = \sum_{i=1}^{n} p^c_i \sin \varphi_i + p^s_i \cos \varphi_i \quad (3.16) \]

where the sine- and cosine-amplitudes of the tidal PM variations are \( p^c_i \) and \( p^s_i \), other symbols correspond to the ones mentioned in Equation 3.14. 60\% of the sub-daily PM variations can be explained by the impact of diurnal and semi-diurnal ocean tides [67]. The remaining variations are caused by non-tidal atmospheric and oceanic effects.

The \textit{a priori} EOPs are obtained from an EOP file by the geodetic VLBI softwares. The most common EOP files used are the IERS C04, finals2000A of USNO and the IVS EOP-S. Finals2000 has both prediction and calculated EOP values, other files use only calculated values. IERS C04 uses Lunar Laser Ranging (LLR), SLR, VLBI, GPS and DORIS data, which are combined. Finals2000A uses VLBI, GPS and Atmospheric Angular Momentum (AAM) data. Both series use both IVS 24-hour and intensive sessions data. IVS EOP-S\(^1\) includes values only from the IVS 24-hour sessions, and, for example, dUT1 has a formal error of about 1 \( \mu s \). 24-hour

\(^1\)http://vlbi.geod.uni-bonn.de/IVS-AC/data/eop-format.txt
geodetic VLBI sessions have a dUT1 accuracy of about 6-7 μs, and intensive sessions have a dUT1 accuracy of about 15 μs, with respect to IERS C04 05 [51].

In the Fortran code for computing the C04 08, the following changes, when compared to the C04 05, were introduced: model for nutation and UT1/LOD tidal variations have been updated to MHB 2000 for precession-nutation, Defraigne and Smits model for tidal variation in UT1/LOD, a new approach for combination of LOD (GPS/SLR data) was developed, compatible with UT1-UTC. Better RMS agreements of the differences between individual and the combined solution, and about 10 μas for long-term polar motion, 3-4 μs for UT1, and 40-50 μas for nutation offsets were obtained[11].

High-frequency EOP are described in IERS Conventions 2003 [57]. The common precession and nutation models are the IAU 2000A [70] and the IAU 2006 [71]. The IAU 2000A precession-nutation theory relates the ICRF to the ITRF and has been effective since January 2003. In 2006, the IAU moved to adopt a more dynamically consistent precession model to complement the IAU 2000A nutation theory [71]. The IAU 2006 has been effective since January 2009.

Daily accuracies for polar motion and precession/nutation in IERS C04 are 0.5 mas, and for dUT1 30 μs. In geodetic VLBI analysis very strong relative constraints of 10⁻⁴ ms/day or mas/day are applied to ensure that the EOP estimates are the same over a session.

### 3.4.5 Solid Earth tides

Solid Earth tides can be described using spherical harmonics. The tidal potential is thus given by (in this example in 2nd degree):

\[
V(r, R) = \frac{GM}{R} \sum_{n=2}^{\infty} \left( \frac{r}{R} \right)^n \cdot P_n(\cos \theta)
\]

(3.18)

where \( G \) is gravitational constant, \( M \) is the mass of the body, \( r \) is the radius of the body, \( R \) is the distance between the centers of mass, \( P_n(\cos \theta) \) are the Legendre polynomials (\( n=0 \) and \( n=1 \) terms cancels out the center of the Earth). \( \theta \) is the angle between the object and the point in question. The term \( n=2 \) causes about 99% of the tidal force, see Table 3.3 [63].

Solid Earth tides are modeled with a tidal potential using Love numbers, \( l, h \), which describe the rigidity/elasticity of the Earth, and thus, vary from

\[\text{ftp://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf}\]
Table 3.3. The effect of solid Earth tides in millimeters caused by the Moon and Sun, degree relates to that of Equation 3.18.

<table>
<thead>
<tr>
<th>degree</th>
<th>Moon</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>425 mm</td>
<td>173 mm</td>
</tr>
<tr>
<td>3</td>
<td>7.5 mm</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>4</td>
<td>0.13 mm</td>
<td>0.00 mm</td>
</tr>
</tbody>
</table>

0 (Earth totally rigid) to 1 (Earth totally elastic). The site displacements due to solid Earth tides are modeled according to the IERS conventions 2010 [57].

3.4.6 Solid Earth pole tide

Polar motion is dominated by the 14-month Chandler wobble and annual variations. It causes effects called solid Earth pole tide and ocean pole tide. Maximum displacements caused by polar motion in the vertical and horizontal direction are, 25 mm and 7 mm [63]. The displacement vector is obtained using Love numbers appropriate to the frequency of the pole tide (h=0.6027, l=0.0836). The variation of station coordinates can amount to a couple of centimeters. In VieVS the instantaneous pole coordinates are corrected for a secular wander of the mean pole [52]. In IERS Conventions 2010 a cubic model is valid until 2010, and is derived by the IERS Earth Orientation Centre and a linear model for extrapolation is used for values after 2010 [57]. For Wettzell the correction in radial component varies from about -8 mm to 7 mm, and for Kokee from about -5 mm to 6 mm [52].

3.4.7 Ocean pole tide

The centrifugal effect of polar motion causes redistribution of ocean mass, which causes a change in loading mass. This can be seen in site position displacement. The ocean pole tide model of Desai (2002) is recommended in the IERS Conventions 2010, and it provides the ocean pole load tide coefficients. Corrections in the radial component, for example, in the case of Wettzell is from about -0.7 mm to 0.5 mm, and in the case of Kokee from -0.3 mm to 0.3 mm [52].
3.4.8 Ocean loading

The elastic response of the Earth’s crust to ocean tides moves the stations up to a few centimeters. Ocean loading consists of 11 main tides; $M_2, S_2, N_2, K_2$ (all with approximately 12-h periods), $K_1, O_1, P_1, Q_1$ (24-h periods), $M_f$ (14 day), $M_m$ (monthly) and $S_{sa}$ (semi-annual). Site displacement due to loading is given by a sum over tides. When modeling ocean loading $\delta$ the following formula is used

$$\delta = \sum_{i=1}^{N} A_{ij} \cos(\omega_i t + V_i - \varphi_{ij})$$ (3.19)

where $\omega_i$ is frequency of tidal constituent $i$ and $V_i$ is astronomical argument of $i$, and they both depend only on ephemerides information; positions of the Sun and Moon [12]. Amplitude $A_{ij}$ and Greenwich phase lag $\varphi_{ij}$ of component $j$ are determined by a model assumed for the deformation of the Earth.

Ocean loading has a period of 12 hours and it varies on a magnitude from millimeters to centimeters. Ocean loading tides have a strong local dependency. For Wettzell ocean tidal loading correction can vary from -6 mm to 6 mm, and for Kokee from -25 mm to 20 mm [52].

The IERS Conventions 2010 method for computing the displacement is an implementation of 342 lesser tides whose amplitudes and phases are found by spline interpolation of the tidal admittances based on the 11 main tides [57].

The commonly used ocean loading model is FES2004 [72], which is a numerical model of the ocean loading tides. The tidal solutions in FES2004 are the result of assimilating satellite altimeter data into a hydrodynamic ocean model.

3.4.9 Non-tidal ocean loading

Non-tidal effects do not have well-known periodic time dependencies, in contrast to the tidal effects which are tied to the motions of the Solar system bodies. Non-tidal effects can be divided into wide-spread and local effects. Wide-spread effects include, for example, atmospheric loading and post-glacial rebound. Local effects are, for example, ground water and snow cover redistribution [12].

For non-tidal ocean loading peak-to-peak variations can reach up to 20 mm in the vertical component, but usually the peak-to-peak variation
of the non-tidal ocean loading is between 2-3 mm in the vertical component. The horizontal displacements are much smaller and the peak-to-peak variation is usually smaller than a millimeter. Non-tidal ocean loading is usually very seasonal and is most significant in coastal regions where the variation in ocean bottom pressure is large. Non-tidal ocean loading has the typical vertical loading RMS values of 0.89 mm for Tsukuba, Japan (a coastal site), and 0.31 mm for Wettzell, Germany (an inland site) [63].

3.4.10 Non-tidal atmospheric loading

Redistribution of air masses due to atmospheric circulation can cause deformation effects of the Earth’s crust on the order of 20 mm for the vertical component and 3 mm for the horizontal component [53]. The oceanic response to atmospheric pressure forcing can be expressed as [53]:

\[
\Delta P_a + \Delta P_w - \Delta P_o = 0
\]  (3.20)

where \(\Delta P_a\) is the variation of local atmosphere pressure, \(\Delta P_w\) is the local variation of the ocean bottom pressure due to induced sea level change, and \(\Delta P_o\) is the mean atmosphere pressure over the world’s oceans, which is applied uniformly at the sea floor. The Petrov and Boy (2004) [53] model is applied in the analysis.

The atmospheric loading is very small for stations located on islands or close to the coast, where the atmosphere is more stable throughout the year in contrast to inland stations. In coastal regions the RMS is below 1 mm and 0.5 mm for the vertical and horizontal components respectively and, for example, for Kokee displacements of 0.5 mm and 0.2 mm have been calculated [53]. For a station located inland, for example, Wettzell displacements of 4.9 mm and 0.9 mm in the vertical and horizontal caused by atmospheric pressure loading have been attained [53].

3.4.11 Tidal atmospheric loading

Tidal atmospheric loading is caused by diurnal heating of the atmosphere which causes surface pressure oscillations. These cause periodic motions of the Earth’s surface. The displacement is modeled with two tidal waves, S1 and S2, and, for example, VieVS uses an external file with cosine and sine components for the Up, North, East deformation [52].

\[http://lacerta.gsfc.nasa.gov/oclo/\]
Atmospheric pressure loading has strong wideband annual and semian-
nual signals, and causes an effect which can have a peak-to-peak am-
plitude of a couple of centimeters. For periods below 10 days the signal is
relatively weak, except for strong S1 and S2 peaks [63].

3.4.12 Ionospheric delay

Ionospheric path delays, $\Delta f_{gr}^{\text{ion}}$, in VLBI for group delay can be calculated
using integrated electron content; the total number of free electrons in a
cylinder with a cross section of 1 m$^2$, and the following formula

$$\Delta f_{gr}^{\text{ion}} = \frac{40.31}{f^2} \text{STEC}$$

(3.21)

where Slant Total Electron Content, $\text{STEC}$, is $10^{16}$ electrons per m$^2$, and $f$
is the frequency, and the unit is meters. If a frequency of 2.3 GHz is used
for the S-band, an ionospheric delay corresponding to 7.6 cm is gained. For
an X-band frequency of 8.4 GHz, the corresponding delay is 0.6 cm.

Ionospheric contribution in the X-band can be expressed as

$$\tau_{gx} = \frac{f_{gs}^2}{f_{gx}^2} (\tau_{gx} - \tau_{gs})$$

(3.22)

where $f_{gs}^2$ and $f_{sx}^2$ are the frequencies for the X- and S-bands, and $\tau_{gx}$ and
$\tau_{gs}$ delays for the two bands.

3.4.13 Neutral atmosphere

In a neutral atmosphere there is no frequency dependency in VLBI obser-
vations like there is in the ionosphere. Delays in a neutral atmosphere
are modeled with ray-tracing, mapping functions and gradients, or
with water vapour radiometry. The influence of asymmetries in the tropo-
spheric delays on $\text{dUT1}$ estimates from intensive sessions is about +/- 10
$\mu$s, but reach 50 $\mu$s during extreme weather conditions [51]. The delay can
be divided into two parts; zenith hydrostatic delay and zenith wet delay.
Zenith hydrostatic delay was described by Saastamoinen (1972) [73] as

$$\Delta L_z = 10^{-6} k_1 \frac{R p_0}{M_d G}$$

(3.23)

where $k_1$ is a locally calculated coefficient, $R$ is the universal gas constant,
$M_d$ is the molar weight of dry air, $p_0$ is total ground pressure, and $G$ is the
gravitational constant.

The formula was refined by Davis et al. (1985) [74] as follows
\[ \Delta L_h = \frac{P_0}{g(\Theta, h)} \]

where \( P_0 \) is pressure and the function \( g(\Theta, h_0) = (1 - 0.00266 \cos(2\Theta) - 2.8 \cdot 10^{-7} \cdot h) \) is used to model the variations of the acceleration due to gravity as a function of the latitude \( \Theta \) (in degree) and the altitude of the station (in meters).

Zenith wet delay varies between 0 cm to, for example, at the poles, 40 cm, and needs to be estimated in VLBI analysis. Mapping functions used to model the path delays caused by the neutral atmosphere are described in the following section.

### 3.4.14 Mapping functions

Mapping functions are a measure of the thickness of the atmosphere. The simplest mapping function, \( mf(\epsilon) = \text{cosecant}(\epsilon) \), where \( \epsilon \) is the elevation angle, is displayed in Figure 3.6. Mapping functions are easiest to compute at higher elevation angles, where the effect of the troposphere is the smallest.

![An example of a simple mapping function, \( mf(\epsilon) = \text{cosecant}(\epsilon) \).](image)

**Figure 3.6.** An example of a simple mapping function, \( mf(\epsilon) = \text{cosecant}(\epsilon) \). Elevation angle of zero degrees is the horizon, and 90 degrees is the zenith.

The concept of a mapping function, \( mf \), is based on separation of the path delays, into a hydrostatic and a wet part [74]:

---

51
\[ \Delta L_e = \Delta L_h \cdot m_f_h(e) + \Delta L^z_w \cdot m_f_w(e) \quad (3.25) \]

\[ \Delta L^z_w = m_f_w(t) + m_f_w(t) \cdot \frac{t - t_1}{t_2 - t_1} \cdot (x_2 - x_1) \quad (3.26) \]

where \( t \) is the epoch of the observation, \( x_1 \) and \( x_2 \) are the continuous piece-wise linear offsets (unknowns) at integer estimation epochs \( t_1 \) and \( t_2 \).

Since troposphere modeling is one of the major error sources in the analysis of VLBI observations, mapping functions which are based on data from numerical weather models, for example, isobaric mapping functions and VMF1, have been developed in recent years.

Mapping functions are hard to compute at low elevation angles. Thus, a 7 degree cutoff angle is used as the limit. Mapping functions need to use an estimation interval of 20 to 60 minutes to allow for least-squares adjustment. Different elevation dependencies exist for zenith delays (mapping functions), clocks, and station heights (sin(e)). Mapping functions are not perfectly known, and the use of low elevations is necessary to de-correlate heights, clocks, and zenith delays. If a mapping function is too large, the zenith delay will be too small, and the station height will be higher than in reality. Wet mapping function is larger than the hydrostatic mapping function.

Modern mapping functions use continued fractions as specified by Herring (1992) [75]

\[ m_f(e) = \frac{1 + \frac{a}{b}}{1 + \frac{1 + c}{a}} \quad \frac{sin(e)}{sin(e) + \frac{b}{sin(e) + c}} \quad (3.27) \]

where \( e \) is elevation angle, \( a, b, c \) are functions of temperature, pressure and elevation. The Herring mapping function is empirical and uses height, latitude, and surface temperature as parameters. Hydrostatic and wet delays are handled separately.

In Vienna Mapping Functions 1 (VMF1), the \( b \) and \( c \) coefficients of the continued fraction form 3.27 for the hydrostatic mapping functions have been redetermined, using 40 years reanalysis data of the European Centre for Medium-range Weather Forecasts (ECMWF). A priori hydrostatic zenith delays are determined from ray tracing through the ECMWF pres-
sure level data, if no pressure values are available for a site [76]. The coefficient $a$ is attained by ray-tracing at an initial elevation angle of 3.3 degrees, and is fitted to a function of latitude and day of year to remove systematic errors, and to determine the correct seasonal and latitude dependence of hydrology. VMF1 uses the best available coefficients $b$ and $c$. The VMF1 are available for all VLBI sites with a resolution of 0.25 degrees. By using VMF1, and its coefficients $a$ and $b$, the mean station heights at the equator and at high latitudes can be more accurately measured. The improvement is about 4 mm [76].

It has been shown that the application of the Vienna Mapping Functions (VMF) instead of the Niell Mapping Functions (NMF) [77] in VLBI analysis improves the repeatability of baseline lengths and significantly changes the TRF [76]. Another commonly used mapping function is the Global Mapping Function (GMF) [78]. Both NMF and GMF are based on pure calculations, and thus, do not take the numerical weather models into account.

When modeling the troposphere, gradients need to be taken into account. Gradients model azimuthal asymmetries in North-South and East-West directions. Gradients are needed because there are local weather phenomena, systematic effects, such as at coastal regions, and to account for higher atmosphere above the equator. In geodetic VLBI analysis, gradients are typically estimated at 6 hour intervals. 1 mm difference in a gradient causes a 100 mm delay at 5 degree elevation. In the analysis, estimates should be constrained to a priori values (different from zero, accounting for the atmospheric bulge above the equator and local effects). GSFC provides static gradients and Technical University of Vienna provides 6 hourly gradients from the ECMWF for the analysts.
Materials and methods
4. Results

4.1 Comparison of UT1 and polar motion from IVS sessions derived from VieVS and Solve analysis

4.1.1 Introduction

The Earth Orientation Parameters (EOPs) are the link between the two reference systems, the Terrestrial Reference Frame (TRF) and the Celestial Reference Frame (CRF). The rotational rate of the Earth is described with UT1; the position of the rotation axis with respect to the CRF is described with nutation and precession, and to the TRF with polar motion. In this research we compare EOP estimates from two software packages. The Calc/Solve analysis software [5] is widely used by the geodetic VLBI community. One of the newer programs is the Vienna VLBI Software (VieVS [4]).

The UT1 and polar motion results obtained by the software packages with their default configurations were compared in two ways. In the first instance, the results were compared when the software packages were employed in their operational modes. Next, the software packages were set up in a new test configuration that maximally synchronized the configuration settings in order to compare the performance of the packages themselves. The effects of altering mapping functions, clock constraints, and a priori EOP files were examined individually.

4.1.2 Materials and methods

The Earth Rotation Parameter (ERP), UT1, and Polar Motion results obtained with the Vienna VLBI Software (VieVS [4]) and Calc/Solve from
both intensive (INT) and 24-hour (R) sessions in 2011 were compared. The formal errors of the estimates, as well as the agreement of the two sets of estimates with the C04 EOP time series, are discussed. A total of 48 INT and 28 R sessions were included in the analysis.

**Handling of the a priori**

The two software packages handle *a prioris* in different ways. Solve uses a clock offset and clock rate, and VieVS employs linear piece-wise offsets at integer hours in the least-squares adjustment. The accuracy of clock offset estimation only depends on the number of observations per session, and the observing geometry does not have any influence on the clock offset itself. The estimability of clock rate improves with the length of the session. For sessions that are considerably longer than intensive sessions the station clocks are not sufficient and a second order clock term as an additional unknown would be necessary [26]. A piece-wise linear function consists of straight line sections.

In Solve a program called GET_APRIORI_EOP retrieves the *a priori* file, either finals.all from the United States Naval Observatory (USNO) or IERS C04 from the International Earth Rotation Service. The program can optionally download a second external EOP file, which then overwrites the values defined in the first external EOP file. There also is an option where the script finds the differences between the retrieved EOP series and the EOP series in erp format used by Solve as the Earth orientation mod-file, finds parameters of linear regression of the differences in UT1, X pole coordinates, Y pole coordinates, then (optionally) subtracts parameters of linear regression from the external EOP series of UT1 and polar motion. Finally, the subroutine GET_APRIORI_EOP reformats the resulting EOP file to 1) ut1pm.dat and to 2) erp-format for Calc and Solve, for use as an Earth orientation mod-file. In VieVS the *a priori* file needs to be downloaded from the VieVS server before analysis. IERS C04 or finals can be used, or the user can use her or his own file, for example EOP-S, after converting it to the VieVS format. IERS C04 EOP series use LLR, SLR, VLBI, GPS and DORIS data, which are combined. Finals uses VLBI, GPS and AAM data. Both series use both IVS 24-hour and intensive sessions data.
<table>
<thead>
<tr>
<th></th>
<th>Default configuration</th>
<th>New configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>VieVS</td>
<td>Solve</td>
</tr>
<tr>
<td>Solution type</td>
<td>Group delay only</td>
<td>Group delay only</td>
</tr>
<tr>
<td>Number of sessions</td>
<td>One standalone</td>
<td>Int: One standalone</td>
</tr>
<tr>
<td></td>
<td>24 h: combined solution</td>
<td>One standalone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Int: One standalone</td>
</tr>
<tr>
<td>Elevation cutoff</td>
<td>0 deg</td>
<td>5 deg</td>
</tr>
<tr>
<td></td>
<td>0 deg</td>
<td>0 deg</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>JPL 421</td>
<td>JPL 405</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JPL 405</td>
</tr>
<tr>
<td>A priori EOP</td>
<td>IERS C04</td>
<td>IERS C04, 24-h: last.erp</td>
</tr>
<tr>
<td>Precession/nutation</td>
<td>IAU 2000A</td>
<td>IAU 2006</td>
</tr>
<tr>
<td>TRF</td>
<td>VTRF2008</td>
<td>Latest operational solution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VTRF2008</td>
</tr>
<tr>
<td>CRF</td>
<td>ICRF2</td>
<td>Latest operational solution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ICRF2</td>
</tr>
<tr>
<td>dUT1 interval, constraint</td>
<td>Int: 60 min, 0.0001 ms/d</td>
<td>One offset, no constraints</td>
</tr>
<tr>
<td></td>
<td>24 h: 1440 min, 0.0001 ms/d</td>
<td>24 h:30 min, 0.0001 ms/d</td>
</tr>
<tr>
<td>ZWD interval, constraint</td>
<td>Int: 60 min, 0.0001 ps²/s</td>
<td>Int: One offset, no constraints</td>
</tr>
<tr>
<td></td>
<td>24 h: 30 min, 0.7 ps²/s</td>
<td>24 h: 20 min, 50 ps/h</td>
</tr>
<tr>
<td>Weighting</td>
<td>no</td>
<td>Baseline weights</td>
</tr>
<tr>
<td>Clock interval, constraint</td>
<td>Int: 1440 min, no const.</td>
<td>Int: no constraints</td>
</tr>
<tr>
<td></td>
<td>24 h: 60 min, 0.5 ps²/s</td>
<td>24 h: 50 fs</td>
</tr>
<tr>
<td>Mapping function</td>
<td>VMF1</td>
<td>NMF, 24-h: VMF1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VMF1</td>
</tr>
</tbody>
</table>

Table 4.1. Configuration of Solve and VieVS software.
Results

Configuration of the programs

Both software packages have very flexible configurations, and the results from the packages depend on the selected configuration settings. At first the programs were run with their default settings for both intensive and 24-hour sessions. Default settings in this context means that the set of models and files used by the software packages is the same as the one used when performing regular analysis of different type of sessions. The models and files differ depending on the software used, and the types of sessions analyzed.

After the default analysis, a new configuration was used where the VieVS and Solve configurations were chosen to be as close to each other as possible by selecting the same models and EOP files for both. For example, in the new configuration both programs used IAU 2000A for precession and nutation, Jet Propulsion Laboratory (JPL) 405 for ephemerides, and Vienna Mapping function (VMF1) as the mapping function. In the new setup VieVS and Solve both used International Earth Rotation and Reference Systems Service (IERS) 05 C04 as the EOP \(a\) priori file, to obtain EOP \(a\) priori values for dUT1, and polar motion. In the default setup Solve used finals2000 from USNO as the \(a\) priori EOP file.

The modelling options for the default settings of the programs and the new configuration are displayed in Table 4.1. All models could not be the same for both software packages. Note that the clock constraint in VieVS for 24-hour sessions is given as a variance, for example, 0.5 ps\(^2\)/s, and for Solve as a standard deviation, for example, 50 fs. For example, if the time interval is 60 min, i.e. there is a variance of 1800 ps\(^2\)/s after one hour, then the standard deviation is 42 ps, and this is the standard deviation used for the observation equation in VieVS [46]. For 24-hour sessions the clock interval is 60 min, and for intensive sessions 1440 min, which is enough to cover the whole session. In normal analysis no clock constraints are applied for the intensive sessions. A variance of 0.5 ps\(^2\)/s would be too tight for short sessions; if only piece-wise linear offsets for clocks are estimated, the software would assume that the clocks do not experience any large drifts, which might not be true.

Typical ZWD constraint values are between 0.1 ps\(^2\)/s and 0.7 ps\(^2\)/s, where the first value is rather small and the latter one describes a strongly varying troposphere [80]. For 24-hour sessions, the latter is applied, and for an intensive session a smaller value is chosen.

A special methodology to bring the epochs to the same point in time was
used. The values for intensive sessions were attained by interpolation to the right epoch. In the case of intensive sessions the epoch was chosen to be the half point of a session, and in case of 24-hour sessions midnight was chosen as the epoch. Midnight is the default epoch in VieVS for 24-hour sessions.

4.1.3 Results

The results concentrating on the automation of the intensive sessions were presented in the poster session of the IVS General Meeting in Madrid, Spain in March, 2012, and a joint article is in print.

The ERP, UT1 and polar motion results, as well as RMS values and differences will be discussed in the following two subsections. The effect of changing models is examined.

**UT1 and polar motion**

A Matlab code was written to visualize the results from both of the software packages, and the two configurations. Figure 4.1 and Figure 4.2 show $d\text{UT1} = \text{UT1}-\text{UTC}$ (in microseconds) estimates from intensive and 24-hour sessions relative to the IERS 05 C04 values. $d\text{UT1}$ estimates were chosen instead of $d\text{UT1}$ values to emphasize the difference in the results of the two software packages and the two setups. The results from both the original setups of the two programs and the new setups are displayed. In Figure 4.3 and Figure 4.4 Xpol and Ypol estimates from the 24-hour adjustment are shown. According to Figures 4.3 and 4.4, the results from both of the programs and the two configurations are similar. However, in Figure 4.2 and in Figure 4.4, some unexpected uncertainties are present. In Figure 4.2 one data point yields a considerably larger $d\text{UT1}$ estimate value than all the other configurations of the software packages. In Figure 4.4 both configurations of VieVS give larger values for the $d\text{UT1}$ estimate at one data point. When investigating the data points more thoroughly, it transpires they are from the same session with MJD of 55645 measured on March 25th, 2011. After reading the correlator report\(^1\) for the session, it was concluded that 44% of the scans were missing: Fortaleza and Hobart did not participate, and the correlator was unable to play back the data due to a failed disk in the disk module.

\(^1\)http://lupus.gsfc.nasa.gov/data10/sessions/2011/r4475/r4475-corrsum.txt
Results

RMS values and differences
Table 4.2 displays a table with the RMS values of the dUT1 estimates relative to their *a priori* values in the Intensive sessions and the dUT1, Xpol, and Ypol estimates relative to their respective *a priori* values in the 24-hour sessions. Also the RMS difference between the solutions is listed (Table 4.2). They are calculated by weighting their individual uncertainties.

When the VieVS and Solve were configured with the new setup, all the RMS values from VieVS deteriorated, as did the RMS results from Solve. The exception was the dUT1 value from the intensive sessions that was slightly improved compared to the default setup. The RMS difference from the dUT1 Intensive estimates improves with the new setup (Table 4.2). Otherwise the RMS differences deteriorate in the case of the 24-hour sessions and the new setup. After eliminating the 24-hour session of March 25th, 2011, a new table was compiled (Table 4.3).

Despite using primarily the same models in the new configuration, VieVS and Solve handle *a priori* in a different way, and as a result almost all results worsen when the default models were changed. In Solve analysis the results for the intensive solution appeared to be better; although the dUT1 estimate improves, the formal error worsens when compared to the values from the default configuration.

Effect of changing a single model
The default setup of the software was altered by changing one model at a time to see its effect on results. The three alterations in the default setup were: 1) changing the mapping function to GMF, 2) changing an *a priori* EOP file to C04 05 or finals2000, and 3) changing the clock constraint option, and were applied to both types of sessions, the intensive and the 24-hour sessions. The changes and the results are listed in Table 4.4. The default configuration of the software packages have changed a bit, for example Solve uses VMF1 instead of NMF and VieVS uses precession/nutation model IAU 2006/2000A instead of IAU 2000A. This has affected the results from the default setups, which now differ from the results presented earlier.

In the dUT1 analysis of the intensive sessions conducted with VieVS, the biggest differences to the results from the default setup arose from using a clock constraint of 0.5 ps²/s. Applying a clock constraint to the Solve intensive session did not affect the results at all. In the default
setup of VieVS for the intensive session analysis, no clock constraint is applied since too tight constraints might cause significant clock drifts to be overlooked. The RMS of the formal error of the dUT1 estimate worsened significantly (from 15.15 $\mu$s to 28.14 $\mu$s), and the RMS of the dUT1 estimate slightly.

Modifying a mapping function from VMF1 to GMF worsened the VieVS results. In the case of the intensive sessions this had the smallest impact, whereas for the 24-hour sessions this had the biggest effect on the results. For the Solve dUT1 analysis, the results from both the intensive and the 24-hour sessions improved slightly when using NMF (GMF is not available in Solve) instead of VMF1. In the Solve polar motion case, altering a mapping function did not affect the results, and only Xpol was slightly affected when the clock constraint was tightened. However, in the VieVS 24-hour analysis, both dUT1 and polar motion RMS values worsened when a tighter clock constraint of 0.1 ps$^2$/s was chosen.

In the Solve analysis changing an a priori EOP file from IERS C04 08 to C04 05 resulted in the largest RMS values for dUT1 and polar motion in both the intensive and 24-hour sessions. In the VieVS analysis, changing the clock constraint, or changing an a priori EOP file to finals2000 had a noticeable effect on all results, as well as using GMF as a mapping function in the case of polar motion results.

In Figures 4.5-4.12 the dUT1 estimates from both the intensive and 24-hour sessions, and Xpol and Ypol from the 24-hour sessions, analyzed with VieVS and Solve, are depicted.

Results from the intensive analysis with VieVS are shown in Figure 4.5. The Solve intensive analysis results are depicted in Figure 4.6. It is evident that all the dUT1 estimate values and formal errors are comparable to each other and that there are only small differences. Figures 4.7 and 4.8 show the dUT1 results from the 24-hour sessions using VieVS and Solve, respectively. Using C04 05 EOP file affects the dUT1 estimate values the most when compared to the values from the other setups of Solve.

Xpol results for both software packages are shown in Figures 4.9 and 4.10. Ypol results are depicted in Figures 4.11 and 4.12. The Tohoku earthquake on MJD 55631, March 11, 2011, causes a jump in Ypol seen in Figures 4.11 and 4.12.
Results

Figure 4.1. dUT1 estimate with respect to the \textit{a priori} IERS 05 C04 calculated from the IVS intensive sessions with VieVS and Solve programs with default and new setups. The dates covered by the analysis are January 1st through February 17th, 2011.

Figure 4.2. dUT1 estimate with respect to the \textit{a priori} IERS 05 C04 calculated from the IVS 24-hour sessions with VieVS and Solve programs with default and new setups. The dates covered by the analysis are January 3rd through March 31st, 2011.
Results

Figure 4.3. Xpol with respect to IERS 05 04 calculated from the IVS 24-hour sessions with VieVS and Solve programs with default and new setups. The dates covered by the analysis are January 3rd through March 31st, 2011.

Figure 4.4. Ypol with respect to IERS 05 04 calculated from the IVS 24-hour sessions with VieVS and Solve programs with default and new setups. The dates covered by the analysis are January 3rd through March 31st, 2011.
<table>
<thead>
<tr>
<th>Software</th>
<th>Default configuration</th>
<th>New configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS of dUT1 estimate (μs), intensive solution</td>
<td>25.56 +/- 13.99</td>
<td>27.90 +/- 15.70</td>
</tr>
<tr>
<td></td>
<td>27.44 +/- 15.48</td>
<td>27.16 +/- 15.51</td>
</tr>
<tr>
<td>RMS of dUT1 estimate (μs), 24 h solution</td>
<td>8.73 +/- 4.01</td>
<td>9.25 +/- 4.15</td>
</tr>
<tr>
<td></td>
<td>9.94 +/- 3.79</td>
<td>9.77 +/- 3.68</td>
</tr>
<tr>
<td>RMS of Xpol estimate (mas), 24 h solution</td>
<td>0.31 +/- 0.15</td>
<td>0.35 +/- 0.16</td>
</tr>
<tr>
<td></td>
<td>0.18 +/- 0.11</td>
<td>0.19 +/- 0.11</td>
</tr>
<tr>
<td>RMS of Ypol estimate (mas), 24 h solution</td>
<td>0.33 +/- 0.11</td>
<td>0.33 +/- 0.12</td>
</tr>
<tr>
<td></td>
<td>0.20 +/- 0.10</td>
<td>0.19 +/- 0.11</td>
</tr>
<tr>
<td>RMS difference of dUT1 estimates (μs), intensive solution</td>
<td>17.51 +/- 4.08</td>
<td>12.68 +/- 3.24</td>
</tr>
<tr>
<td>RMS difference of dUT1 estimates (μs), 24 h solution</td>
<td>12.32 +/- 1.48</td>
<td>17.40 +/- 2.34</td>
</tr>
<tr>
<td>RMS difference of Xpol estimates (mas), 24 h solution</td>
<td>0.25 +/- 0.058</td>
<td>0.25 +/- 0.098</td>
</tr>
<tr>
<td>RMS difference of Ypol estimates (mas), 24 h solution</td>
<td>0.29 +/- 0.045</td>
<td>0.35 +/- 0.058</td>
</tr>
</tbody>
</table>

Table 4.2. Comparison of VieVS and Solve RMS values, and RMS difference between the two software for dUT1, and polar motion estimates.
### Table 4.3.
Comparison of VieVS and Solve RMS values, and RMS difference between the two software for dUT1, and polar motion estimates after outlier elimination.

<table>
<thead>
<tr>
<th>Software</th>
<th>Default configuration</th>
<th>New configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VieVS</td>
<td>Solve</td>
</tr>
<tr>
<td>RMS of dUT1 estimate ($\mu$s), 24 h solution</td>
<td>7.58 +/- 3.93</td>
<td>9.63 +/- 3.77</td>
</tr>
<tr>
<td>RMS of Xpol estimate (mas), 24 h solution</td>
<td>0.32 +/- 0.15</td>
<td>0.24 +/- 0.15</td>
</tr>
<tr>
<td>RMS of Ypol estimate (mas), 24 h solution</td>
<td>0.29 +/- 0.11</td>
<td>0.21 +/- 0.10</td>
</tr>
<tr>
<td>RMS difference of dUT1 estimates ($\mu$s), 24 h solution</td>
<td>9.88 +/- 1.49</td>
<td></td>
</tr>
<tr>
<td>RMS difference of Xpol estimates (mas), 24 h solution</td>
<td>0.25 +/- 0.059</td>
<td></td>
</tr>
<tr>
<td>RMS difference of Ypol estimates (mas), 24 h solution</td>
<td>0.25 +/- 0.045</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4. Effect of changing models on dUT1 and polar motion from intensive and 24-hour sessions. finals2000 and GMF could not be used in Solve analysis. NMF was used instead of GMF in Solve analysis.
Results

Figure 4.5. Effect of changing a model in dUT1 analysis with VieVS from intensive sessions.

Figure 4.6. Effect of changing a model in dUT1 analysis with Solve from intensive sessions.
Results

Figure 4.7. Effect of changing a model in dUT1 analysis with VieVS from 24-hour sessions. Changed model is marked in legend.

Figure 4.8. Effect of changing a model in dUT1 analysis with Solve from 24-hour sessions. Changed model is marked in legend.
Figure 4.9. Effect of changing a model in Xpol analysis with VieVS from 24-hour sessions. Changed model is marked in legend.

Figure 4.10. Effect of changing a model in Xpol analysis with Solve from 24-hour sessions. Changed model is marked in legend.
Results

Figure 4.11. Effect of changing a model in Ypol analysis with VieVS from 24-hour sessions. Changed model is marked in legend.

Figure 4.12. Effect of changing a model in Ypol analysis with Solve from 24-hour sessions. Changed model is marked in legend.
4.1.4 Conclusions

Almost all of the RMS values worsen for both programs when using the new configuration (Figure 4.2). When looking at the RMS difference between the two programs, they only improve for the intensive solution of Solve when applying the new configuration.

After the elimination of a single 24-hour session measured on March 25th, 2011, all the RMS values of dUT1 estimates and their formal errors were reduced, except the formal error of the dUT1 estimated by the new configuration of Solve. The RMS values of the Xpol and Ypol estimates for both configurations of Solve grew, and the RMS value of the Ypol estimate for the default configuration of VieVS was decreased. Other values remained almost unchanged. RMS differences of dUT1 and Ypol deteriorated, while the RMS difference of Xpol remained almost the same as without the elimination. With the elimination the new configuration the RMS values decreased for Solve. The RMS difference of the new configurations of dUT1 estimates were reduced to 57% of the original values with the elimination of the single session.

On the basis of this analysis it appears that VieVS gives smaller RMS values for UT1, and Solve does the same for polar motion when using the default configurations of the two programs. However, the comparison of the software packages is still difficult, which was also noted in [81] and [82] where VieVS, Solve, C5++, SteeleBreeze and Occam were compared.

In VieVS analysis changing a mapping function to GMF, or a priori EOP file to finals2000, had a small negative impact on dUT1 results for both intensive and 24-hour sessions. In Solve the RMS value of the dUT1 estimate slightly improved when NMF was chosen instead of VMF1. Böhm and Schuh [83] have concluded that for intensive sessions changing a mapping function (in their case from NMF to VMF1) does not affect dUT1 estimate results significantly, since mapping function errors mainly affect the height component of the stations. They analyzed all Kokee - Wettzell, and Tsukuba - Wettzell intensive sessions in 2006 using OCCAM. The influence on dUT1 difference was below +/- 1.5 μs for all sessions. Both VieVS and Solve results are in good agreement with the results of Böhm and Schuh, and it can be concluded that changing to a different mapping function has a rather small influence on dUT1. However, it is surprising that changing to the NMF in the Solve analysis improved the results. VMF1 uses numerical weather models and pressure data at a site,
and should result in more accurate results than the NMF which is based purely on calculations.

Changing the *a priori* EOP file to C04 05 improved the dUT1 estimate slightly for the 24-hour sessions using VieVS, whereas it worsened the results for both the 24-hour and the IVS sessions using Solve, as expected. In fact, in Solve it had the largest negative impact on the results. In VieVS using a clock constraint of 0.5 ps$^2$/s for the intensive sessions had the largest effect; the RMS of the formal error was twice that of the default setup. In VieVS the effect on polar motion results, in general, was somewhat larger than the impact on dUT1 estimates derived from the 24-hour sessions. For polar motion results derived using Solve, only changing the EOP file had a significant effect.

VieVS and Solve handle the *a priori* s differently; Solve uses a clock offset and clock rate, and VieVS employs linear piece-wise offsets at integer hours in the least-squares adjustment. In VieVS using a clock constraint for dUT1 analysis from intensive sessions, and tightening the clock constraint in the case of 24-hour sessions, gave the worst results. In Solve changing the clock constraint did not have an effect on the results, except that there was a slight improvement in the RMS value of Xpol. In Solve analysis changing the EOP file had the worst effect.

This research shows that the results from the two software packages are affected by different modeling options. However, the differences to the results from the default setups are rather small and within the error limits. It can be concluded that using the models described in the IERS Conventions 2010, and used by the software in their default configuration is advisable.

### 4.1.5 Future work

The 24-hour solution RMS difference decreased after the elimination of a single session. However, the configurations of VieVS and Solve could possibly be brought closer to each other. To verify the results obtained during this research, the number of sessions could be increased from the 48 intensive and the 28 24-hour sessions used here. It would also be worthwhile to compare the results to those obtained by another technique, such as GNSS.


4.2 Influence of source distribution on UT1 derived from IVS INT1 sessions

4.2.1 Introduction

The influence of the spatial distribution of the observations on the quality of UT1 results derived from IVS [3] INT1 sessions is explored. The Kokee-Wettzell baseline midpoint was chosen as a reference point for the analysis. A Matlab code was written for classification of the topocentric source positions in different sections of the sky, as seen from the reference point. A combination of these key numbers was then used to classify the sessions with quality codes and compare them with their respective formal errors. Preliminary results concentrating on IERS C04 as the *a priori* EOP were presented at the IVS General Meeting in Madrid, Spain in March, 2012, and a joint article submitted to the conference proceedings in April, 2012. The results obtained in the research were presented at the EVGA Meeting in Espoo, Finland in March, 2013, and another proceedings article is in preparation. A joint article to be sent to a peer-reviewed scientific journal will also be written. The results of the research will be compared to those of the GSFC group’s results [84], [85] and [86]. However, in earlier research, the reference point was Kokee Park North direction, and not the midpoint of the baseline, which makes this investigation, and its results novel.

4.2.2 Materials and methods

The effect of the source constellations on the quality of the dUT1 results is examined. IVS intensive sessions INT1 with the baseline Kokee-Wettzell were chosen for the analysis because these sessions are measured five times per week, and therefore there are enough data to obtain reasonable results.

A fictitious baseline reference point is defined as the projection of the baseline midpoint onto the ellipsoid and serves as the origin of a topocentric system with the tangential plane being the equatorial plane of this system; see Figure 4.13. The baseline system can be interpreted as a hemisphere put on top of the ellipsoid at the baseline reference point (Figure 4.13).

There are several other reasons to include low elevation sources when scheduling intensive sessions. It is necessary to include observations with
different elevation angles, to distinguish between the elevation dependent tropospheric delay and the clock parameters, which are independent of elevation. Observations with low elevation angles are essential for the estimation of the tropospheric path delay. Several tests with intensive session observing schedules showed that the inclusion of 20 to 30% low declination sources (≤ 25 degrees) is associated with an improvement of the theoretical UT1 sigmas of about 45% in average [26].

The precision of the Zenith Wet Delay (ZWD) estimates for characteristic times of order 20 minutes improves as data are included from lower elevation angles. However, systematic errors on the timescale of a day, due to errors in the mapping functions, for example, will increase significantly when observations at elevation angles somewhere below 10 degrees are added to the solutions [88] [89].

INT1 sessions would benefit from an improved handling of the unknown atmosphere with, for example, water vapor radiometer or GPS data, because due to the long baseline the possibility of observing enough sources under varying elevation angles is strongly limited, and thus the estimability of the atmospheric path delay suffers [26]. Also, there are usually gaps in the observing schedules [90] because most stations also use their antennas for astronomical observations, which means that additional atmospheric data relating from other techniques is valuable.

Both the horizon limits of the two stations and the observations are best displayed in a stereographic projection, which is created by the SkyPlot program and described in in the following section.
SkyPlot program
The SkyPlot program, written in GNU Octave, produces azimuth-elevation text files for the purpose of plotting station and baseline dependent sky plots. Skd files are used as input files, which are produced with the software package SKED [91]. The skd files contain the scheduled observations of a session and information about the station and source positions as well. The required information is parsed and used to calculate azimuth and elevation per scan for each participating station. These data are saved in ASCII files. Furthermore, an output file is created per baseline as seen from the perspective of a fictitious telescope placed at the baseline midpoint. In addition, the horizon limits of the stations are converted to the respective baseline midpoints by three sequenced single rotations. The common horizon of two stations at their baseline midpoint is the connecting line of the greatest elevation values per azimuth. Only radio sources above this border can be observed by both telescopes simultaneously. Plotting the baseline-dependent sky plot as a stereographic projection, like the one shown in Figure 4.14, the area of no visibility is shaded in gray. The cusps of the white area (sky sections 1 and 2 in Figure 4.14), the area of common visibility, are the lowest elevations for both stations. The azimuth-elevation text files created by the SkyPlot program are used as the input files for the Matlab program written for the analysis.

Analysis strategy
The stereographic projection from the SkyPlot program was divided into six sections as shown in the Figure 4.14. The azimuth and elevation limits are calculated on the basis of the azimuth - elevation files from the Skyplot. The files have the values in the format of azimuth = -azimuth + \(\pi/2\) and elevation = \(\pi/2\) - elevation, because of plotting reasons. The azimuth limits for sections 1, 3 and 5 are: \(\pi/2 > azimuth \geq -\pi/2\)

and for sections 2, 4 and 6,

\(-\pi/2 > azimuth \geq -3\pi/2\).

The elevation limits are in sections 1 and 2,

\(\pi/2 > elevation \geq \pi/3\),

in sections 3 and 4,

\(\pi/3 > elevation \geq \pi/6\)

and in sections 5 and 6,

\(\pi/6 > elevation \geq 0\).

Quality codes AA-D are assigned when 1 or more sources in two sections
Results on opposite parts of the sky are seen from the midpoint of the baseline.

![Stereographical projection with the division to different sky sections](image)

**Figure 4.14.** Stereographical projection with the division to different sky sections. Division to sections 1-6 was done with azimuth and elevation values obtained from the SkyPlot program.

- AA is assigned if there are two sources in one of the sections 1 and 2, and two or more sources in the other. Quality code A is assigned, if there is one source in one of the two sections, and one or more in the other.

- BBB is assigned if there are three or more sources either in sections 1 and 4, or 2 and 3. BB is assigned if there are two sources in one of the sections (1 and 4, or 2 and 3), and two or more in the other. B is assigned if there is one source in one of the sections, and one or more in the other.

- Quality code C is assigned, if there are three or more sources in sections 3 and 4.

- If any of the quality codes from AA to C cannot be assigned (if there are not enough sources in any of the section pairs to enable the session to get a code AA-C), quality code D is assigned.

See Figure 4.15, for the section pairs.

600 INT1 sessions with the baseline Kokee - Wettzell from January 2009 to October 2011 were included in the analysis. 569 of these sessions were observed and correlated. After removing outliers (> 100 µs) 544 sessions were included in the analysis. Standard VLBI data analysis was performed following the IERS Conventions 2010 [57] with the Vienna VLBI Software (VieVS [4]). A Matlab program was written to divide the data into different sections, to give quality codes and to calculate session counts.
4.2.3 Results

dUT1 estimates with respect to the \textit{a priori} IERS C04 dUT1 [92], and IVS EOP-S [3] dUT1 and their formal errors were calculated with VieVS and quality code error plots were generated to see at which level the formal errors of each category lay. Mean values, session counts, and mean scan counts for the results in each category were calculated. IVS EOP-S was used because its results do not already include IVS intensive sessions, as IERS C04 do, but it includes values from the IVS 24-hour sessions.

Quality code error plots

Quality code error plots were drawn to determine at which level the formal errors are in different quality categories. The session counts in each category can be evaluated based on Figure 4.16. The data were divided into seven quality categories: AA, A, BBB, BB, B, C and D. Only four sessions were classified as AA. As is evident in Figure 4.16, the variation in the formal errors increases from AA to D. The variation is the smallest for
Table 4.5. Models used in the Vienna VLBI Software (VieVS) analysis.

<table>
<thead>
<tr>
<th>TRF</th>
<th>VTRF2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRF</td>
<td>ICRF2008</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>JPL 421</td>
</tr>
<tr>
<td>EOP</td>
<td>C04</td>
</tr>
<tr>
<td>Mapping function</td>
<td>VMF1</td>
</tr>
<tr>
<td>Precession/nutation</td>
<td>IAU 2000A</td>
</tr>
<tr>
<td>Elevation cutoff</td>
<td>no elevation cutoff used</td>
</tr>
<tr>
<td>Hf EOP</td>
<td>IERS conv. 2003</td>
</tr>
<tr>
<td>Ocean loading</td>
<td>FES2004</td>
</tr>
<tr>
<td>Atmospheric loading</td>
<td>yes</td>
</tr>
<tr>
<td>Large clock errors</td>
<td>one offset per clock</td>
</tr>
<tr>
<td>Clock parametrization</td>
<td>PWLOs/clock, const 0.5 ps²/s, interval 360 min</td>
</tr>
<tr>
<td>Troposphere</td>
<td>ZWD constraint 0.0001 ps²/s, interval 60 min</td>
</tr>
<tr>
<td>dUT1</td>
<td>Interval 60 min</td>
</tr>
</tbody>
</table>

The quality codes and session mean scan counts, both before and after outlier elimination, are listed in Table 4.6. The mean scan count is about 22-24 scans per session for categories BBB-C, and for AA-A about 19-21 scans per session. Category D has the lowest scan counts both before and after the outlier elimination, 17.30 and 18.60 scans per session. A total number of 544 sessions were analyzed with respect to the IVS EOP-S after the elimination of outliers. In Table 4.6, categories B, C and D have the highest percentage of removed sessions due to outliers, 5.7 %, 4.8 % and 7.0 %, respectively. The mean scan counts for the sessions which have outliers increase after the elimination. It is striking that categories AA-BBB have no outliers (dUT1 difference to EOP-S or its formal error does not exceed 100 μs), and BB has only one outlier.

Figure 4.17 shows the dUT1 difference with respect to the EOP-S a priori for different categories, AA-D. The sessions in category AA are concentrated in the +/- 20 μs region. The BBB category has the second smallest variation in the dUT1 difference.
Table 4.6. Quality code counts, code count without outlier elimination, number of outliers, the percentage of data with outliers (removed from the analysis) per code count, and mean scan counts before and after outlier elimination for each category AA-D.

<table>
<thead>
<tr>
<th>Code</th>
<th>AA</th>
<th>A</th>
<th>BBB</th>
<th>BB</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>4</td>
<td>79</td>
<td>39</td>
<td>73</td>
<td>106</td>
<td>145</td>
<td>115</td>
</tr>
<tr>
<td>Outliers</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>% of outliers</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>5.7</td>
<td>4.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Scans (before)</td>
<td>21.00</td>
<td>19.46</td>
<td>22.74</td>
<td>22.07</td>
<td>22.03</td>
<td>22.41</td>
<td>17.30</td>
</tr>
<tr>
<td>Scans (after)</td>
<td>21.00</td>
<td>19.46</td>
<td>22.74</td>
<td>22.38</td>
<td>23.35</td>
<td>23.54</td>
<td>18.60</td>
</tr>
</tbody>
</table>

RMS difference and quality code counts

The mean Formal Error (FE) of the dUT1 estimates and RMS difference for dUT1 estimates with respect to IERS C04 for each quality code are listed in Table 4.7. The RMS difference for dUT1 from the intensive analysis with respect to the combined solution from IVS EOP-S are listed in the fourth column of Table 4.7. The category AA gives the best result. Also listed are the mean differences between C04 and EOP-S. Before the elimination of the outliers the mean values of the formal errors grow from AA-D in that order. When the outliers are removed, categories AA and A still give the best results.

Codes C and D have the largest mean values of formal errors of the dUT1 estimates with respect to a priori IVS EOP-S. The mean values of formal errors are the smallest with quality codes AA and BBB.

When the outlier limit was set to > 100 $\mu$s for formal error, all categories except AA, A and BBB had outliers, and the category BB had only one outlier. For the only four sessions with quality code AA, their mean formal error is 21.7 $\mu$s, with an RMS difference of 9.3 $\mu$s to C04, and an RMS difference of 25.3 $\mu$s compared to IVS EOP-S dUT1 (Table 4.7).

After the outlier elimination the RMS values of the dUT1 with respect to EOP-S, for example with category C and D, dropped to from 93.0 $\mu$s to 29.0 $\mu$s, and from 66.8 $\mu$s to 38.3 $\mu$s, after the elimination of the outliers.

In Table 4.8 the median values for the formal errors of dUT1 differences with respect to EOP-S are displayed for each of the quality codes, AA-D. Because the categories AA-BBB did not include any outliers, the median values remained the same before and after the elimination.

Category, A, with sources in the furthest down cusps, has the smallest
Results

Figure 4.16. Formal errors of dUT1 estimates compared to IVS EOP-S \textit{a priori} and quality code counts for categories AA, A, BBB, BB, B, C, and D, in that order. On X-axis is the session count, and on the Y-axis the formal error in $\mu$s.

Figure 4.17. dUT1 estimates compared to IVS EOP-S \textit{a priori} and quality code counts for categories AA, A, BBB, BB, B, C, and D, in that order. On X-axis is the session count, and on the Y-axis the dUT1 difference to EOP-S in $\mu$s.

median (the category AA comes in second place), but the largest mean when excluding categories C and D with the sources clustered in the mid region of the sky. This can be explained by the small mean scan count, 21.00 for AA, and 19.46 for A. On the basis of this research, two separate things affect the dUT1 formal error accuracy, the source distribution and the number of scans per session.

98.80% of the scheduled scans were observed and correlated. Failed sessions are not included in this percentage, only successfully correlated scans of successful sessions. The scheduled and observed scans were derived from SKD and NGS files, respectively.
Table 4.7. Mean formal error of the dUT1 difference, RMS difference to IERS C04, RMS difference to IVS EOP-S, mean difference to C04 and to EOP-S, all results with the values before outlier elimination in parentheses for each code, AA-D in $\mu$s.

<table>
<thead>
<tr>
<th>Code</th>
<th>Mean FE</th>
<th>RMS C04</th>
<th>RMS EOP-S</th>
<th>Mean C04</th>
<th>Mean EOP-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>21.7</td>
<td>9.3</td>
<td>25.4</td>
<td>-3.6</td>
<td>7.0</td>
</tr>
<tr>
<td>A</td>
<td>22.9</td>
<td>27.5</td>
<td>40.5</td>
<td>-8.7</td>
<td>-10.1</td>
</tr>
<tr>
<td>BBB</td>
<td>25.4</td>
<td>22.8</td>
<td>31.6</td>
<td>-4.4</td>
<td>-1.9</td>
</tr>
<tr>
<td>BB</td>
<td>27.0 (29.4)</td>
<td>27.2</td>
<td>34.3 (34.7)</td>
<td>-7.5</td>
<td>-3.2 (-2.4)</td>
</tr>
<tr>
<td>B</td>
<td>25.7 (31.8)</td>
<td>28.5</td>
<td>31.7 (39.8)</td>
<td>-2.3</td>
<td>-0.5 (-1.5)</td>
</tr>
<tr>
<td>C</td>
<td>25.0 (33.4)</td>
<td>33.7</td>
<td>29.0 (93.0)</td>
<td>-0.9</td>
<td>-0.9 (7.8)</td>
</tr>
<tr>
<td>D</td>
<td>29.1 (38.0)</td>
<td>32.0</td>
<td>38.3 (66.8)</td>
<td>-6.0</td>
<td>-12.1 (-14.1)</td>
</tr>
</tbody>
</table>

Table 4.8. Median formal errors for each code, AA-D in $\mu$s after outlier elimination, the values before the elimination in parentheses.

<table>
<thead>
<tr>
<th>Quality code</th>
<th>Median of the formal errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>24.7</td>
</tr>
<tr>
<td>A</td>
<td>19.1</td>
</tr>
<tr>
<td>BBB</td>
<td>20.4</td>
</tr>
<tr>
<td>BB</td>
<td>23.2 (23.7)</td>
</tr>
<tr>
<td>B</td>
<td>22.1 (22.9)</td>
</tr>
<tr>
<td>C</td>
<td>24.6 (25.6)</td>
</tr>
<tr>
<td>D</td>
<td>27.0 (28.0)</td>
</tr>
</tbody>
</table>

Figure 4.18 displays the dUT1 difference derived from the IVS INT1 sessions compared to the IVS EOP-S a priori, and Figure 4.19 shows the dUT1 calculated from the EOP-S a priori with the outliers removed ($> 100 \mu s$). The sessions from the worst category D, marked in blue in the figures, have the largest difference compared to the EOP-S. They also have large formal errors together with sessions in the B and C categories.
Figure 4.18. dUT1 difference with respect to IVS EOP-S derived from IVS INT1 in milliseconds from January 2009 to October 2011. The symbols are labelled at the right of the plot.
Figure 4.19. dUT1 with respect to IVS EOP-S derived from IVS INT1 in seconds from January 2009 to October 2011. The symbols are labelled at the right of the plot.
**Midpoint sky plots**

In Figures 4.20 through 4.26 midpoint sky plots for quality codes AA - D are drawn. The values of the formal errors and scan counts of the sessions are written in the captions of the figures. The subplots of these figures are organized as follows:

- **left in top row** the sky plot of the session with the smallest formal error of dUT1 difference to IVS EOP-S,
- **right in top row** a sky plot with the formal error close to the median of the formal errors of the quality code,
- **left in bottom row** a sky plot with the formal error larger than the median,
- **right in bottom row** the sky plot with the largest formal error.

These sky plots require detailed analysis in order to define what makes some source distributions give more accurate results than others. It was first supposed that the sky plots with the smallest formal errors would have the sources evenly scattered across the sky.

In Figures 4.20 - 4.22 it is evident that the evenly scattered source distributions result in smaller formal errors. With sessions in categories BB-D the sources are more clustered in the middle of the sky by the definition of the categories, and the results are not as easily concluded as with categories AA-BBB.

In Figure 4.20 to 4.24, in each of the categories the smallest formal error of the dUT1 difference compared to the IVS EOP-S *a priori* is achieved with the evenly scattered sources. Categories C and D have a source distribution with sources clustered in the mid region of the sky as seen from the midpoint of the baseline. Their dUT1 RMS values with respect to both IERS C04 and IVS EOP-S are the largest, as are the mean formal errors.

From the sky plots in Figure 4.20 - Figure 4.26, and the scan count for each session, it is concluded that the dUT1 values together with their formal errors depend on the source distribution, and even a large number of scans per session will not result in more accurate formal errors if the sources are clustered in the middle of the sky.

### 4.2.4 Conclusions

600 INT1 observing sessions were categorized with respect to their geometric distribution of observations in a baseline-fixed reference system.
Category AA with observations far down in the baseline sky plot cusps appeared to be the best one, while categories from BB to D with hardly any observations in the cusps, or almost all observations close to the zenith of the baseline, are the worst. The formal errors appeared to be convincingly low in categories AA, A and BBB with only very few values larger than 20 μs, and their mean formal errors are the best of all categories (Figure 4.16). This is to be expected because of the good geometry of the sessions. Better sky coverage is known to be linked with improved precision and accuracy of the UT1 estimates as mentioned in [86]. It is important to note that the categories AA-BBB have no outliers (dUT1 difference to EOP-S or its formal error does not exceed 100 μs), and BB has only one outlier. The scan count improves after the outlier elimination, which implies that the larger scan counts result in better accuracy as the RMS values became smaller. Categories A and D have the smallest scan counts. After the outlier elimination B and C have the largest scan counts. When looking at the RMS of the dUT1 estimates with the respect to the EOP-S, it is evident that the scan counts do affect the results. However, the RMS value for category AA is clearly the best regardless of its smaller scan count.

Larger formal errors definitely appeared more frequently in categories BB and below, with formal errors often reaching 20 μs and above. From Figure 4.16, the sessions with the largest formal errors usually lay in the left sides of the subplots, and thus were measured in 2009. Some improvement has already been made in the scheduling with more evenly scattered sources and larger scan counts, which has resulted in smaller formal errors. In future work the sessions in categories AA and A will be analyzed individually and the reasons leading to larger dUT1 estimates and formal errors will be investigated. For example, troposphere or bad sources could worsen the results in spite of an even source distribution. Our research strongly implies that scheduling sources to the far down cusps is essential in improving the accuracy of dUT1.
Figure 4.20. Sky plots for AA: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (10.4 μs), formal errors in the middle region on right in top row (23.7 μs) and left in bottom row (25.8 μs), largest formal error with the sky plot on right in bottom row (26.9 μs). The number of scans for these sessions are 18, 22, 22 and 22.

Figure 4.21. Sky plots for A: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (8.9 μs), formal errors in the middle region on right in top row (19.1 μs) and left in bottom row (35.2 μs), largest formal error with the sky plot on right in bottom row (88.4 μs). The number of scans for these sessions are 17, 18, 17 and 22.
Figure 4.22. Sky plots for BBB: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (8.4 $\mu$s), formal errors in the middle region on right in top row (20.4 $\mu$s) and left in bottom row (45.2 $\mu$s), largest formal error with the sky plot on right in bottom row (75.8 $\mu$s). The number of scans for these sessions are 21, 28, 33 and 23.

Figure 4.23. Sky plots for BB: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (7.2 $\mu$s), formal errors in the middle region on right in top row (24.0 $\mu$s) and left in bottom row (40.7 $\mu$s), largest formal error with the sky plot on right in bottom row (74.5 $\mu$s). The number of scans for these sessions are 21, 20, 19 and 24.
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Figure 4.24. Sky plots for B: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (13.2 $\mu$s), formal errors in the middle region on right in top row (21.2 $\mu$s) and left in bottom row (44.8 $\mu$s), largest formal error with the sky plot on right in bottom row (95.5 $\mu$s). The number of scans for these sessions are 19, 22, 34 and 24.

Figure 4.25. Sky plots for C: smallest formal error of dUT1 difference compared to IVS EOP-S with the sky plot on left in top row (7.2 $\mu$s), formal errors in the middle region on right in top row (23.7 $\mu$s) and left in bottom row (42.2 $\mu$s), largest formal error with the sky plot on right in bottom row (56.8 $\mu$s). The number of scans for these sessions are 21, 24, 27 and 27.
The results of this research are in good agreement with the GSFC group's results ([84], [86] and [85]) when it comes to maximizing the number of scans per sessions. It is obvious from Table 4.6, that after the outlier elimination the mean scan counts increase. This implies that smaller scan counts result in poorer dUT1 estimates and formal errors. In [86] better sky coverage and a larger number of sources in the test strategy resulted in a 30% better average of the UT1 formal errors. However, in [84], [85] and [86], the sky was observed in the Kokee Park North direction, and not from the midpoint of the baseline, which makes this research, and its results, unique. If the reference point is not located at the midpoint of the baseline, it is harder to obtain a uniform sky coverage. From Figures 4.20-4.26 it is obvious, that the source distribution plays a more important role than the number of scans per session when it comes to the accuracy of the dUT1 estimate, as almost all of the sessions with the smallest formal errors have the least scans when compared to other sessions in their categories.

Observations in the baseline sky plot cusps are important for the geometric stability of the estimation of UT1-UTC from Intensive sessions, because these observations appear to reduce the danger of large formal errors even more. They should, thus, be scheduled with highest priority.
4.2.5 Future work

A proposal to schedule a dedicated IVS Research and Development session will be written in which special attention will be drawn to source distribution. In the near future a recommendation for the IVS will be given on the basis of this research on scheduling the IVS intensive sessions with the source distribution concentrating on multiple sources in the farthest most cusps of the sky as seen from the midpoint of the baseline, with evenly scattered sources, as well as the number of scans, taken into account. Also simulations to study geometry’s impact on formal errors could be performed.

4.3 Automated analysis of UT1 from IVS Intensive sessions with the Vienna VLBI Software

In the next generation VLBI system, VLBI2010 [1], one of the most important requirements is automating the analysis process. In the research conducted, the Vienna VLBI Software (VieVS [4]) was automated to analyze IVS intensive sessions to derive the dUT1 parameter. The results on the automation of intensive sessions were partially presented in the poster session of the IVS General Meeting in Madrid, Spain in March, 2012, and an article was sent to the conference proceedings, in April, 2012. In the future, when VieVS is implemented with the currently unavailable pre-analysis steps, ambiguity resolution and ionospheric correction, also the analysis of IVS 24-hour sessions can be automated.

4.3.1 Introduction

The Vienna VLBI Software (VieVS [4]) version 1d was used in its batch mode to analyze IVS intensive sessions automatically to derive the Earth Orientation Parameter (EOP) dUT1. The automation process uses a shell script that is run daily by a cron process. The goal is to achieve dUT1 results as soon as the NGS file is fetched from the VieVS server.

Three types of analysis strategies, called S-1, S-2 and S-3, were used in the process to compare different parameterizations and to improve the latency of deriving dUT1. The S-1 analysis strategy uses as \textit{a priori} Earth orientation parameters the values provided by the U.S. Naval Observa-
Results

tory (USNO) EOP-file finals2000A2, uses the Global Mapping Function (GMF) [78] as mapping function, and does not apply atmospheric loading. The S-2 analysis strategy differs from the first analysis strategy by using the Vienna Mapping function (VMF1 [76]) as its mapping function instead of the GMF and by applying atmospheric loading. The S-3 analysis strategy differed from the second approach by using the IERS C04 [92] values as \textit{a priori} Earth orientation parameters. All other parameters were treated identically for the three analysis strategies.

The latency of the results for the first analysis strategy is 2-3 days from the end of a session and is dominated by the time that is necessary to correlate the observational data and to pre-process the data, i.e. to provide a NGS file3 where group delay ambiguities are resolved and the ionospheric effects are corrected. The latency of the results for the second strategy is slightly worse, about 3-4 days, mainly due to the time that it takes until VMF1 and atmospheric loading based on ECMWF4 analysis data are available because they use several days of weather data. The latency of the results for the third strategy is even worse, about 30 days, and is dominated by the time that it takes until the IERS C04 data are available. The latencies are described in Figure 4.27.

The RMS values of the formal errors of the three strategies in the case of INT1 sessions are 15.6, 15.4 and 15.0 $\mu$s for strategy 1, 2 and 3, respectively. The formal error of S-3 is the best, but the latency is the worst. To enhance the latency of S-1, we currently work on including the necessary preprocessing steps, i.e. group delay ambiguity resolution and ionospheric correction, directly into VieVS. The results of the automated analysis are provided both as data files and in graphical form on the Metsähovi web pages

- http://www.metsahovi.fi/vlbi/vievs/
- .../results_GMF
- .../results_VMFI
- .../results_C04, respectively.

3http://lacerta.gsfc.nasa.gov/mk5/help/dbngs_format.txt
4http://www.ecmwf.int/
### 4.3.2 Materials and methods

**IVS intensive sessions and modelling options**

The automation process uses a shell script that is run daily by a cron process. The goal is to achieve dUT1 results as soon as the observed delays are available as an NGS file. Three types of analysis strategies (S-1, S-2, S-3) are used in the process in order to compare different modeling options. The different modeling options used for the different strategies are listed in Table 4.9. All other models are identical for the S-1, S-2 and S-3, see Table 4.10.

In the analysis two different mapping functions are used; GMF and VMF1. It has been shown that the updated VMF, called VMF1, based on new coefficients, yields slightly better baseline length repeatabilities for VLBI data than VMF [76]. The other mapping function used in this analysis is the GMF, based on data from the global ECMWF numerical weather model. The coefficients of the GMF have been obtained from an expansion of the VMF1 parameters into spherical harmonics on a global grid. Similar to NMF, the values of the coefficients require only the station coordinates and the day of year as input parameters. Compared to

<table>
<thead>
<tr>
<th></th>
<th><strong>S-1</strong></th>
<th><strong>S-2</strong></th>
<th><strong>S-3</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Finals</strong></td>
<td>(no latency)</td>
<td>(no latency)</td>
<td>C04 (add ~30 days to latency)</td>
</tr>
<tr>
<td>No atmos. loading</td>
<td>(no latency)</td>
<td>atmos. loading</td>
<td>atmos. loading</td>
</tr>
<tr>
<td>(latency 3-4 days)</td>
<td>(latency 3-4 days)</td>
<td>(latency 3-4 days)</td>
<td></td>
</tr>
<tr>
<td>GMF</td>
<td>(no latency)</td>
<td>VM1</td>
<td>VM1</td>
</tr>
<tr>
<td>(latency 2-3 days)</td>
<td>(latency 2-3 days)</td>
<td>(latency 2-3 days)</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 4.27. The three analysis strategies, their EOP files and models, and their latencies. NGS file version 4 causes a latency of approximately 2-3 days for S-1. The use of atmospheric loading and VMF1, causes a latency of 3-4 days for S-2, because they both use weather information from ECMWF. S-3 has a latency of about 30 days, due to the C04 EOP file, which does not include prediction values as finals.*
the 6-hourly values of the VMF1, a slight degradation in short-term precision occurs using the GMF. The biggest advantage of using the GMF in the automation is that because it is based on pure calculations, it does not add any latency. The regional height biases and annual errors of NMF are significantly reduced with GMF [78].

Table 4.9. Modelling options for strategies S-1, S-2 and S-3.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A priori EOP</td>
<td>USNO finals2000A</td>
<td>USNO finals2000A</td>
<td>IERS C04</td>
</tr>
<tr>
<td>Mapping function</td>
<td>GMF</td>
<td>VMF1</td>
<td>VMF1</td>
</tr>
<tr>
<td>Atm. loading</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 4.10. Other models used.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRF</td>
<td>VTRF2008</td>
</tr>
<tr>
<td>CRF</td>
<td>ICRF2</td>
</tr>
<tr>
<td>Ephemerides</td>
<td>JPL421</td>
</tr>
<tr>
<td>Precession/nutation</td>
<td>IAU 2000A</td>
</tr>
<tr>
<td>Elevation cutoff</td>
<td>no elevation cutoff used</td>
</tr>
<tr>
<td>Hf EOP</td>
<td>IERS conv. 2003</td>
</tr>
<tr>
<td>Ocean loading</td>
<td>FES2004</td>
</tr>
</tbody>
</table>

Implementation of ambiguity resolution and ionospheric correction to Vienna VLBI Software

The current version 2.0 of the Vienna VLBI Software (VieVS [4]) does not include all the analysis steps introduced in the Calc/Solve software [5]. VieVS uses NGS card5 version number 4s, which means that when using VieVS, one is not independent of Calc/Solve. In order to use NGS version 2 cards, additional steps need to be included in the VieVS. These steps are called ‘Group ambiguity resolution’ and ‘Ionospheric correction’.

Ambiguity estimation is an iterative process that involves the computation of a simplified geodetic solution and shifting of the ambiguities according to the residuals obtained. Closure conditions need to be considered (Figure 4.28) in order to make sure that ambiguities are distributed over all existing baselines without evoking inconsistencies in the station.

5http://lacerta.gsfc.nasa.gov/mk5/help/dbngs_format.txt
Results

The difficult part of the ambiguity estimation is to align the ambiguities in a way that does not only match the observed delays, but also considers all closure conditions (in Figure 4.28 one example for such a condition: ambiguities must be aligned in a way which closes the triangle spanned by stations A, C and D) [48].

![Figure 4.28. Triangle closures for five station network (modified from [48]).](image)

**Ambiguity resolution in VieVS**

The group delay ambiguities depend on the minimum spacing between channels in the band synthesis, and is typically 50-200 ns [47]. For example, in S-Band for an R1 experiment the BBCs have the following frequencies: 2225.99 MHz, 2245.99 MHz, 2265.99 MHz, 2295.99 MHz, 2345.99 MHz, and 2365.99 MHz.

The spacings between the BBC frequencies in this case are:

\[
2365.99 - 2345.99 = 20 \text{ MHz}, \ 2365.99 - 2295.99 = 70 \text{ MHz}, \ 2365.99 - 2265.99 = 100 \text{ MHz}, \ 2365.99 - 2245.99 = 120 \text{ MHz}, \ \text{and} \ 2365.99 - 2225.99 = 170 \text{ MHz}
\]

The minimum spacing is 20 MHz for the S-band in the R1 sessions with these settings. This means that the ambiguities will be at \(1/(20 \times 10^6 [\text{Hz}])\) = 50 ns.

Resolving the group delay ambiguities with VieVS consists of several steps (following [94]):

- A reference clock station is picked.

- The clocks for the other stations are parameterized with a single offset and rate for the entire experiment.
• The delays are downweighted in a way that they will not confuse the solution.

• The delay rates are examined. They should show strong banding about the delay ambiguities.

• The delays are moved to a single ambiguity which is closest to zero for all baselines involving the reference clock station.

• The procedure is repeated for all the remaining stations.

• Ionospheric correction.

4.3.3 Results

RMS results
The RMS values of the adjustments with respect to the a priori dUT1 values, and the average values of the formal errors for the three analysis strategies, are listed in Table 4.11. As the latency became worse, the variation of dUT1 decreased. In order to improve the latency of strategy S-1 we are currently working on including the necessary pre-processing steps, i.e. group delay ambiguity resolution and ionospheric corrections, directly into VieVS.

Table 4.11. Impact for the three different analysis strategies S-1, S-2 and S-3 on the dUT1 estimates for both INT1 and INT2/INT3 sessions: Average formal errors of the dUT1 estimates, and WRMS agreement of the dUT1 estimates with respect to IERS C04 dUT1 values.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1 (μs)</th>
<th>S-2 (μs)</th>
<th>S-3 (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INT1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average formal error</td>
<td>15.6</td>
<td>15.4</td>
<td>15.0</td>
</tr>
<tr>
<td>WRMS w.r.t. IERS C04</td>
<td>62.6</td>
<td>55.8</td>
<td>21.0</td>
</tr>
<tr>
<td>INT2/3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average formal error</td>
<td>25.4</td>
<td>23.52</td>
<td>27.2</td>
</tr>
<tr>
<td>WRMS w.r.t. IERS C04</td>
<td>27.7</td>
<td>36.9</td>
<td>25.8</td>
</tr>
</tbody>
</table>
Figure 4.30 and Figure 4.29 depict the dUT1 results for both INT1, and INT2 and INT3 sessions, using the three different strategies. Strategies S-1 and S-2 use *a priori* Earth orientation parameters (EOP) from USNO finals2000A. Usually, these values are predicted EOP, resulting in the data plotted with red dots. In case of additional delays, e.g. late availability of NGS files, the USNO finals2000A has been updated already by final EOP. Results obtained using these *a priori* are shown with green dots.

The results of the automated analysis are provided both as data files and in graphical form on the Metsähovi Radio Observatory web pages:

- http://www.metsahovi.fi/vlbi/vievs/results_GMF
- .../results_VMF1
- .../results_C04
- .../latest_dut1_S-1+S-2+S-3_XK.png
- .../latest_dut1_S-1+S-2+S-3_XU.png

respectively.

RMS values of the INT1 and INT2/3 sessions for all three analysis strategies are provided on the web page:

http://www.metsahovi.fi/vlbi/vievs/latest_RMS+WRMS.txt

A leap second was introduced in June 2012, which causes a jump in Figure 4.30 and Figure 4.29. From the INT1 results, S-1 gave the largest formal error average value (15.6 microseconds), and S-3 the smallest (15.0 microseconds). The WRMS value of the corrections to the dUT1 *a priori* values was smallest with S-3 (21.0 microseconds), and largest with S-1 (62.6 microseconds). ECMWF and C04 data are not convenient when a short latency is required. In case of the INT2/3 results, S-2 gave the smallest formal error (23.5 microseconds), and S-3 the largest (27.2 microseconds). dUT1 estimate was the smallest with S-3 (25.8 microseconds), and the largest with S-2 (36.9 microseconds). The higher WRMS values for INT1 sessions analyzed with S-1 and S-2 compared to the INT2/3 sessions can be explained with passing percentage by outlier criteria. Only about 25% of the S-1 and S-2 INT2/3 session pass the outlier criteria; values larger that 0.2 ms for dUT1 estimate and 0.1 ms for formal error, or
Results

Figure 4.29. dUT1 from INT2 and INT3, with baselines Wettzell - Tsukuba, Wettzell - Tsukuba - Ny Ålesund, respectively, and using strategies S-1, S-2 and S-3. Red and green dots indicate that the a priori EOP from USNO finals2000A were either predicted EOP (red) or final EOP (green). The data points are connected with lines because otherwise it would be difficult to distinguish different strategies from each other.

Figure 4.30. dUT1 from INT1 with a baseline Wettzell - Kokee using strategies S-1, S-2 and S-3. Red and green dots indicate that the a priori EOP from USNO finals2000A were either predicted EOP (red) or final EOP (green). The data points are connected with lines because otherwise it would be difficult to distinguish different strategies from each other.

if formal error is for some reason zero. The same percentage for INT1 sessions is about 80%. A large RMS of INT UT1 with respect to predicted is not a problem; large deviation in the RMS shows the necessity of VLBI
Ambiguity resolution is handled within the modified VIE_LSM program. An example of an ambiguity resolution plot drawn with the vie_lsm.m program modified in this research is given in Figure 4.31, where an ambiguity of 50 ns is clearly seen.

With the Graphical User Interface (GUI) developed in the present study, a user can select the files for both S and X frequency bands to be handled by the software. Also the parameter file is chosen with the GUI. Because the NGS version 2 card for S frequency is used for the ionospheric correction, it is necessary to select the correct cards for both S and X frequency bands. When the NGS files and the correct parameter file are chosen, the user will push the 'Ok' button for the analysis to start.

In the Ambiguity Resolution And Ionospheric Correction (ARAIC) GUI displayed in Figure 4.32, the user first needs to choose the data directory where the NGS cards to be processed are saved. After selecting the directory, the NGS cards can be chosen. The selected NGS files appear in the right-most box. The parameter file is chosen with the box below the folder selection box. It is necessary to use the correct parameter file that
4.3.4 Conclusions

From the results in Table 4.11 it is concluded that the average formal errors of the results of all three strategies are close to each other, with a slight improvement in S-3 in the case of INT1 sessions. This can be explained with the notion that the dUT1 results are already included in the IERS C04 a priori dUT1 values, and do not include prediction values. In S-1 GMF and the choice not to use atmospheric loading reduce the latency of results, and when compared to S-2 and S-3, give comparable formal error values. However, the RMS with respect to IERS C04 gives the best dUT1 estimate values of all session types. It cannot be concluded on the basis of this research, which affects the results most, the use of GMF instead of VMF1, or not using an atmospheric loading model, or both. The use of the a priori prediction values worsens the dUT1 estimates, and can explain the larger values in S-1 and S-2 results.

While taking a closer look at the INT2 and INT3 dUT1 results and their formal errors, it was noticed that the INT2 results after the Tohoku earthquake still are rather poor, as the results from the INT3 are clearly more accurate due to Ny Ålesund also included in the experiments. This could clearly be seen on the following web page with the RMS, WRMS and mean...
values for the results, when looking at the percentage of the sessions that passed the quality limits:

http://www.metsahovi.fi/vlbi/vievs/latest_RMS+WRMS.txt

All of the INT2/INT3 sessions taken into account for these results are in fact INT3 experiments. A follow up study on the INT2/INT3 is being performed at the moment, and will be presented at the EVGA meeting in Espoo, Finland in March, 2013. In the follow up study new a priori coordinates for Tsukuba will be added to VieVS analysis automatically. This should immediately improve the current results for INT2/INT3 sessions.

4.3.5 Future work

In order to prove which worsens the RMS with respect to the IERS C04 values, for the S-1 strategy, the use of the GMF or not using the atmospheric loading model, the data could be re-analyzed employing two new strategies: one with the use of GMF and atmospheric loading, and the other with the use of VMF1 and no atmospheric loading.

In the future the script could also be implemented to analyze IVS 24-hour sessions (R1 and R4). In this case the ambiguity resolution and ionospheric correction step need to be automated in VieVS. It has already been done with C5++ [48].

It is necessary to complete the Vienna VLBI Software (VieVS) with the currently unavailable pre-processing steps from the latest version 2.0, for the software to be completely independent of Calc/Solve. Previously the user had to wait for the NGS version 4 cards to be downloaded. This caused a delay of a couple of days in the analysis results, and the user had to use files which already were pre-processed by another person, and thus could include some unwanted errors in the data. Adding ambiguity resolution and ionospheric correction steps into VieVS makes the analysis independent of Calc/Solve, removes the unwanted delay and possible errors caused by a Calc/Solve analyst, who has pre-processed the version 2 NGS cards and created the version 4 ones. Reducing the latency of the NGS version 4 cards is necessary, especially when analyzing the Earth orientation parameter dUT1.

In its current version of the implementation developed in this research, the group delay ambiguities are solved for a single baseline, and for either X- or S-band. More work needs still to be performed to have the program working first for intensive sessions, and later for experiments with multiple baselines. The main part of the software is already finished, which
will only need to be combined and extended.

4.3.6 Automation script

The shell script written for the automation process is in Appendix A.

4.4 FX correlator inside FILA10G board

The FILA10G device is an FPGA based board, with a main purpose of transferring VLBI data from the DBBC [6] to the ethernet with the use of 2 x 10 Gbps XFP bi-directional optical outputs. In addition it is possible to use 2 x 1, 2, or 4 Gbps SFX connections for general-purpose applications. The inputs can be selected from four different VSI-H connections, or from the DBBC HSI for pure sampled data coming from the ADB board.

To perform zero baseline correlation tests for the evaluation of proper VLBI observing conditions, a new VHDL firmware was written. To enable such tests, a complex cross correlator firmware was coded. Because the FILA10G has a Virtex4 FPGA [95] with two PowerPCs, it was the perfect environment to download the firmware into.

In an FX correlator the Fourier transform is performed first, and the complex multiplication after that, in an XF correlator the cycle of operations is the opposite. For example, the VLBA correlator [96] is of an FX type, and the Mark 4 [97] is a XF one. FX was chosen over XF, because the FX architecture minimizes the number of operations to perform the task, by using an efficient FFT algorithm [96]. The FX correlator inside the FILA10G board will be used for autocorrelation purposes.

4.4.1 Introduction

The FILA10G acts as the digital interface between the DBBC and the external world. It is a 10G optical fibre ethernet board, and has a triangle connection between the HSI, VSI and 10G link. The FILA10G main features are:

- Two independent 10G ethernet UDP ports
- Physical interface through optical XFP transmitters

6http://www.vlbi.org/vsi
Results

- Fully bi-directional 10G ports
- Installed within the DBBC, or can be used as a standalone device
- Data rate 1, 2, 4, or 8 Gbps for each 10G port
- Formats: MK5B in two 5008 packets, or VDIF-ST in any allowed packet sizes

In the stand-alone version of the FILA10G, communication is handled through the serial port, or the ethernet. The FILA10G files at the moment are:

- timesyncFILA10G.exe, MK5B time set
- vdif_timesyncFILA10G.exe, VDIF time set
- sendstr.exe, for serial communication
- FILA10G_v2.bit, to download the firmware

4.4.2 Materials and methods

Firmware implementation

The FX complex cross-correlator firmware inside the FILA10G board was written in VHDL, and consists of 5 blocks: the input channel selection of two channels, delay, two complex FFTs, complex multiplication, and integration with numerical data output for visualization. The block diagram of the FX correlator inside the FILA10G board is displayed in Figure 4.33.

VLBI data is recorded in sign and magnitude sampling, where the sign is represented with a sign bit and magnitude in a magnitude bit. The sign and magnitude codes are described in Mark5B users manual\(^7\) and are listed in 4.12. Sampling at 1-bit produces an SNR of about 0.63 and sampling at 2-bit produces an SNR of about 0.87, while the ideal SNR is 1.0. To maximize SNR when data-rate is constrained, it is best to increase the bandwidth and use 2-bit sampling. A simple example of sampling at

\(^7\)http://www.haystack.edu/tech/vlbi/mark5/docs/
Figure 4.33. The block diagram of the FX correlator inside the FILA10G.

2-bits per sample is shown in Figure 4.34.

Table 4.12. The sign and magnitude codes in Mark5B format.

<table>
<thead>
<tr>
<th>BBC output (mv)</th>
<th>Sign</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 220</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0 → 220</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0 → -220</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>&gt; -220</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.34. An example of sampling at 2-bits/sample.

- Block 1: Input channel selection
The two FILA10G input source data streams can be chosen by the user with the firmware.

- **Block 2: Delay**
  Delay in a range of 0 to 511 clock cycles was added after the selection of the input channels. With the delay it is ensured that the data has time to adjust. In future the delay can be set by the user.

- **Block 3: FFT**
  The FX correlator Fourier transforms the signal (equation for $s_i(\nu)$ from [96]):

  $$s_i(\nu) = \int_{-\infty}^{+\infty} X_i(t)e^{-i2\pi\nu t}dt$$  
  (4.1)

  where $e$ is the mathematical constant, that is the base of the natural logarithm and $\pi$ is the mathematical constant that is the ratio of a circle’s circumference to its diameter.

- **Block 4: Complex multiplication**
  The station spectra from Equation 4.1 are then cross-multiplied (equation for $S_{ij}(\nu)$ [96]):

  $$S_{ij}(\nu) = s_i(\nu)s_j^*(\nu)$$  
  (4.2)

- **Block 5: Integration**
  The cross-power spectrum in Equation 4.2 is then integrated. A number of samples of the data are gathered, and a mean of these is calculated. In the future, number of samples will defined by the user.

The sign and magnitude information for both channels is saved to an array of 256 bits. A delay in range of 0 to 511 clock cycles can be chosen before the FFT process. The results from the complex multiplication is saved to an array of 512 bits for both channels.

**Channel selection**
- Inputs: vsi_clk, the two channels selected by the user: channel_A, vsi_data_in_A, and channel_B, vsi_data_in_B
- Outputs: the sign and mag information for the channels
Results

Delay

• Inputs: vsi_clk, delay_A, delay_B, A_sign_mag and B_sign_mag,

• Outputs: The wanted delays to the stream: delayed_A_8 and delayed_B_8,

Complex Fast Fourier Transform

• Input signals in time domain with the delayed signals: delayed_A_8 and delayed_B_8

• Output signal in frequency domain: A_real, A_imag, and B_real, B_imag

Two independent FFTs were inserted in the firmware to move from the time domain into the frequency domain. Two FFT components were created with the Core Generator in the Xilinx ISE software\(^8\). The options for the FFTs are displayed in the screenshots of the Core Generator GUIs in Figure 4.35 - Figure 4.37.

\(^8\)[http://www.xilinx.com/products/design-tools/ise-design-suite/]

Figure 4.35. The FFT options GUI 1.

• BW is 32 MHz: with 512 points we get 256 frequency points with 0.5 MHz for each band
Results

Figure 4.36. The FFT options GUI 2.

Figure 4.37. The FFT options GUI 3.

- **Target clock**: 64 MHz
- **Data format**: fixed point
- **Input data width**: the minimum (8) was chosen and zeroes put where not needed (we have 3-bit representation)
• Phase factor: zero, minimum was 8 -> zeroed

• Natural ordering

Complex multiplication
• Input from the two FFTs: A_real, A_imag, and B_real, B_imag

• Output: buff_real and buff_imag

The complex multiplication in the VHDL code is performed with Equations 4.3 and 4.4:

\[
\text{multi}_\text{real} = A_{\text{real}} \times B_{\text{real}} - A_{\text{imag}} \times B_{\text{imag}} \quad (4.3)
\]

\[
\text{multi}_\text{imag} = A_{\text{real}} \times B_{\text{imag}} + A_{\text{imag}} \times B_{\text{real}} \quad (4.4)
\]

Integration
• Inputs are the outputs from the multipliers: buff_real and buff_imag

• Output: a mean of several results

4.4.3 ISE timing results

The firmware was successfully synthesized with the Xilinx ISE Project Navigator program. The firmware was compiled without any errors. Because there were no FILA10G boards available at MPIfR, final testing within the FPGA inside the board could not yet be conducted. Below is the timing report from the ISE program.

Timing Summary:

Speed Grade: -12
Minimum period: 3.162ns (Maximum Frequency: 316.251MHz)
Minimum input arrival time before clock: 5.309ns
Maximum output required time after clock: 3.793ns
Maximum combinational path delay: 4.790ns
4.4.4 Conclusions

It is important for the user at a VLBI station to monitor the quality of the data when needed. For this purpose zero baseline tests become useful. The firmware developed can be downloaded to the FPGA inside the FILA10G board or the standalone version of the FILA10G used as the ethernet board for the DBBC. The functionality implemented by the code is a useful contribution to assure that the backend present in the radiotelescopes, typically very far from one another, are coherently able to process signals received with the interferometric VLBI method. The amendments developed in this research will be tested, and verified at MPIfR, and after that implemented at the VLBI stations with a DBBC and a FILA10G. At the moment due to the lack of FILA10G boards, the testing within the FPGA inside the board is not possible.

4.4.5 Future work

In the near future two implementations could be conducted, the data could to be written to a file in numerical form, and after that it could be visualized.

Numerical output for visualization
A numerical output will be written to get the frequency response (magnitude and phase with the respect to frequency).

Matlab code for visualization
Data can be visualized, for example, with Matlab, Octave, or IDL. Amplitude and phase can be plotted with respect to frequency.

4.4.6 VHDL code

The firmware developed in this study is written Appendix B.
5. Conclusions and future work

5.1 Conclusions

Partly based on the research conducted in Chapters 4.1-4.3 three articles were submitted to the conference proceedings of the IVS General Meeting in Madrid, Spain, in 2012. Also, two presentations of the research described in Chapters 4.2 and 4.3 were be given at the EVGA meeting in March, 2013, in Espoo, Finland. In addition to these, two articles to be sent to peer-reviewed international scientific journals are planned, based on the research in Chapters 4.2 and 4.3.

If the IVS data analysis centers will use only one software package, the results can be biased. Thus, newer software packages than Calc/Solve are required for the geodetic community. The comparison of Calc/Solve and VieVS in Chapter 4.1 shows that it is even possible to obtain more accurate dUT1 results from both IVS 24-hour and intensive sessions with VieVS than with Solve, although it seemed that polar motion results have a better precision with Solve than with VieVS. When VieVS is implemented with the now-missing pre-analysis steps, it can be used independently of Calc/Solve.

For the next generation geodetic VLBI system, VLBI2010, three requirements of great importance include improving the accuracy of the dUT1 parameter, reducing the latency of the data analysis results, and improving VLBI data quality by using digital backends.

By scheduling IVS intensive sessions with multiple sources in the cusps farthest down as seen from the baseline midpoint, having an evenly scattered source distribution and large enough scan count will ensure the best accuracy for both dUT1 difference to a priori from EOP-S, and its formal error. It is quite striking that there are no outliers in the categories which
have multiple sources in the farthest-down cusps. These sessions with most sources in the cusps have substantially better UT1 estimates and significantly smaller formal errors.

Earlier investigations have not observed the sky from the baseline mid-point, which makes this research and its results unique. A recommendation for the IVS on scheduling intensive sessions in the future will be given on the basis of this research. The accuracy of GNSS positioning is related to the accuracy of the EOP; thus, if the dUT1 accuracy is improved, it will affect everyone using a GPS receiver, as navigational aids are used in aviation, shipping, and terrestrial transportation. The results of the research are in good agreement with those of the GSFC group’s results ([84], [85] and [86]) when it comes to maximizing the number of scans per sessions. However, in [84], [85] and [86], the sky was viewed from the Kokee North direction, and not from the midpoint of the baseline. If the midpoint is not used as the reference point, a uniform source distribution cannot be scheduled. The results are significant because they prove that there still is room for improvement in the IVS scheduling of the intensive sessions due to the new approach developed.

Automatic analysis with the Vienna VLBI software developed in this thesis, and implementing it with the pre-analysis steps that are currently in development, will reduce the latency. Automatic analysis of IVS intensive sessions was completed during research for this thesis. C5++ has already been automated to analyze both intensive and 24-hour sessions [49] [48], which implies that the automation of VieVS for the 24-hour sessions is also feasible.

Checking the quality of the VLBI data in real time with the zero baseline tests using the DBBC and the FILA10G, and the firmware written in this dissertation will improve the data. The functionality implemented by the firmware is a useful contribution to ensure that the backends present in the radiotelescopes, typically very far from one another, are coherently able to process signals received with the interferometric VLBI method. The firmware has been successfully synthesized, but due to the lack of FILA10G boards at EVN stations, it has not yet been tested within the board.
5.2 Future work

Comparison of UT1 and polar motion from IVS sessions derived from VieVS and Solve analysis

More data, both from IVS intensive and 24-hour sessions, should be analyzed to ensure the results from the study. In addition, a comparison with GPS data would be useful over a time scale of a year or more. Also, dUT1 from intensive sessions would benefit from being inspected with respect to other EOP series (for example as was undertaken in other research for this thesis for IVS EOP-S).

Influence of source distribution on UT1 derived from IVS INT1 sessions

A proposal to schedule dedicated research and development sessions using IVS stations will be written in which special attention to having sources in far down cusps will be given. In the near future a recommendation for the IVS will be given on how to schedule the IVS intensive sessions. The source distribution should have multiple sources in the farthest-most cusps of the sky as seen from the midpoint of the baseline. The sources should also be evenly scattered and the number of scans should be taken into account.

A way to distinguish high and low quality sessions based on the source distribution and the number of correlated scans per session using a specific algorithm was determined. The algorithm could be included, for example, in the VieVS or other geodetic VLBI software if necessary. Validation results will be published later in a joint paper by all the contributors.

Automated analysis of UT1 from IVS Intensive sessions with the Vienna VLBI Software

In the future the script could be implemented to analyze IVS 24-hour sessions (R1 and R4). A conference article concentrating on the follow-up study of the automation analysis results is in preparation.

In the future the group delay ambiguity resolution and ionospheric correction will be tested with 24 h sessions, and included in the VieVS. The one baseline version of the script has showed promising results.
FX correlator inside FILA10G board

The preliminary tests have been conducted, and the firmware was successfully synthesized. Due to the lack of available FILA10G boards, the test results will be verified at MPIfR when more boards are available. After validation, the firmware will be implemented at VLBI stations with a DBBC and a FILA10G. In the near future, there’s the possibility of implementing two versions of the firmware where the data will not only be written to files in numerical form but will also be visualized.
References


References


[82] Plank, L.: Results from the VLBI Data Analysis Software Comparison Campaign, presented at VieVS User Workshop, in Vienna, Austria, 7-9 September, 2010.


A. VieVS automation script developed in this study
#!/bin/bash
set -e

resultsdirbase="/home/www/www.metsahovi.fi/documentroot/vlbi/views"
viewsdirdir=$HOME/VieVS_1d/VieVS
password=$(cat $HOME/.views-password)
matlab="ssh matlab matlab -nosplash -nodisplay"

function update_data() {
  # Get new NGS data files
  /rsync-with-password $password users@vievsg,hg.tuwien.ac.at:NGS/DATA/NGS $viewsdirdir/DATA
  /rsync-with-password $password users@vievsg,hg.tuwien.ac.at:NGS/VM1 $viewsdirdir
  /rsync-with-password $password users@vievsg,hg.tuwien.ac.at:NGS/ATM $viewsdirdir
  /rsync-with-password $password users@vievsg,hg.tuwien.ac.at:NGS/EOP $viewsdirdir

  # Update information about earth orientation parameters (EOPs)

  wget --no-cache -O $viewsdirdir/EOP/C04_08_1962_now.txt.tmp
  grep "^[0-9]" < $viewsdirdir/EOP/C04_08_1962_now.txt.tmp > $viewsdirdir/EOP/C04_08_1962_now.txt.tmp
  grep "^[0-9]" < $viewsdirdir/EOP/C04_08_1962_now.txt.tmp > $viewsdirdir/EOP/C04_08
}

function process_data() {
  paramfile="$1"
  resultsdir="$2"
  for i in $(cd $viewsdirdir/DATA/NGS && find 2* -mindepth 1 -maxdepth 1 -type f -name "????????X[UK]_N???" -mtime -100); do
    # i="2011/11APR23XK_N003"
    year=$(echo $i | cut -d"-" -f1)
    session=$(basename $i)
    resultsfile=$viewsdirdir/DATA/LEVEL3/test/x_$session.mat
    rm -f "$resultsfile"
    resultsdir2=$resultsdir/$year/$session
    if [ -d $resultsdir ]; then
      echo skipping $i
      continue
    fi
    echo processing $i
    echo "process_list = [ 'i' ]; save($viewsdirdir/WORK/process_list.mat, 'process_list'); quit;" | $matlab
    cp -v "$paramfile" "$viewsdirdir/DATA/LEVEL0/test/$session_parameter.mat"
    t=$<mktemp>
    echo "cd $viewsdirdir/WORK; views('batch'); quit;" | $matlab 2>&1 & tee $t
    if [ -e $resultsfile ]; then
      echo "failed"
      rm $t
      continue
    fi
    if [ ! -d "$resultsdir2" ]; then
      mkdir -p "$resultsdir2"
    fi
    cp -v $viewsdirdir/EOP/finals2000A.data $resultsdir2
    gzip -9 $resultsdir2/finals2000A.data
    cp -v $resultsfile $resultsdir2
    echo "load($viewsdirdir/DATA/LEVEL3/test/x_$session.mat, 'x_'); disp(sprintf('nmjd=%f\ndt1_diff=%f\nerr=%f\n', x_.dt1.mjd(1), x_.dt1.val(1), x_.dt1.mx(1))); quit;" | $matlab | grep = > $resultsdir2/short.txt
    chmod a+r $t
    mv $t $resultsdir2/log.txt
  done
}
update_data
process_data $viesdir/WORK/PARAMETERS/Finals_VM1_parameter.mat $resultsdirbase/results_VM1
process_data $viesdir/WORK/PARAMETERS/Finals_GMF_parameter.mat $resultsdirbase/results_GMF
process_data $viesdir/WORK/PARAMETERS/C04_parameter.mat $resultsdirbase/results_C04

echo "matlab;vbi-vievs;0;processed $files" | /usr/sbin/send_nsca -H nagios -d ";" | grep -v "sent to host successfully"
VieVS automation script developed in this study
B. VHDL code for zero baseline tests developed in this research
-- Company: MPIfR
-- Engineer: Minttu Uunila
-- (c)
-- Create Date:
-- Design Name:
-- Module Name: vhdl_top - Behavioral
-- Project Name:
-- Target Devices:
-- Tool versions:
-- Description:
--
--The FX complex cross-correlator inside the Fila10G board consists of 5 blocks--
--Block 1: Input channel selection--
--Block 2: Delay--
--Block 3: FFT--
--Block 4: Complex multiplication--
--Block 5: Integration--
--
-- Dependencies:
--
-- Revision:
-- Revision 0.01 - File Created
-- Additional Comments:
--
----------------------------------------------------------------------------------------
library IEEE;
use ieee.std_logic_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
--use IEEE.STD_LOGIC_UNSIGNED.ALL;

use ieee.std_logic_signed.all;
use ieee.math_real.all;

library UNISIM;
use UNISIM.VComponents.all;

--library ieee_proposed;
--use ieee_proposed.fixed_pkg.all;

--library STD;
use STD.textio.all;

entity vhdl_top is

Port (    sys_clk_pin : IN std_logic; -- 50/100 MHz microprocessor clock    sys_rst_pin : IN std_logic; -- reset    fpga_0_RS232_Uart_1_RX_pin : IN std_logic; -- rs232 rx    fpga_0_RS232_Uart_1_TX_pin : OUT std_logic; -- rs232 tx

-- to be used for data coming from vsi-----------------------------------------------
vsi1_in_data64_p : in std_logic_vector(63 downto 0); -- external data input vsi1
vsi1_in_data64_n : in std_logic_vector(63 downto 0); -- external data input vsi1

vsi1_1pps_i_p : in std_logic; -- 1pps in vsi1
vsi1_1pps_i_n : in std_logic; -- 1pps in vsi1

vsi2_1pps_i_p : in std_logic; -- 1pps in vsi2
vsi2_1pps_i_n : in std_logic; -- 1pps in vsi2

vsi1_valid_i_p : in std_logic; -- external data input validity vsi1
vsi1_valid_i_n : in std_logic; -- external data input validity vsi1

vsi2_valid_i_p : in std_logic; -- external data input validity vsi2
vsi2_valid_i_n : in std_logic; -- external data input validity vsi2

-- to be used with clk coming from vsi1---------------------------------

vsi1_clkbuf_i_p : in std_logic; -- external clock in vsi1(128 MHz max in VLBI)
vsi1_clkbuf_i_n : in std_logic; -- external clock in vsi1(128 MHz max in VLBI)

--
clkbuf_pin : in std_logic; -- proto-board external clock

vsi2_clkbuf_i_p : in std_logic; -- external clock in vsi2(128 MHz max in VLBI)
vsi2_clkbuf_i_n : in std_logic; -- external clock in vsi2(128 MHz max in VLBI)

vsi1_data64_o_p : out std_logic_vector(63 downto 0); -- external data output vsi1
vsi1_data64_o_n : out std_logic_vector(63 downto 0); -- external data output vsi1

vsi1_1pps_o_p : out std_logic; -- 1pps out vsi1
vsi1_1pps_o_n : out std_logic; -- 1pps out vsi1s

vsi2_1pps_o_p : out std_logic; -- 1pps out vsi2
vsi2_1pps_o_n : out std_logic; -- 1pps out vsi2

vsi1_valid_o_p : out std_logic; -- external data input validity vsi1
vsi1_valid_o_n : out std_logic; -- external data input validity vsi1

vsi2_valid_o_p : out std_logic; -- external data output validity vsi2
vsi2_valid_o_n : out std_logic; -- external data output validity vsi2

vsi1_clkbuf_o_p : out std_logic; -- external clock out vsi1(128 MHz max in VLBI)
vsi1_clkbuf_o_n : out std_logic; -- external clock out vsi1(128 MHz max in VLBI)


vsi2_clkbuf_o_p : out std_logic; -- external clock out vsi2(128 MHz max in VLBI)
vsi2_clkbuf_o_n : out std_logic--; -- external clock out vsi2(128 MHz max in VLBI)
);

end vhdl_top;

architecture Behavioral of vhdl_top is
component myPC
port(
    -- General sysclk, rs232, clk, res
    fpga_0_rst_1_sys_rst_pin : IN std_logic;
    fpga_0_clk_1_sys_clk_pin : IN std_logic;
    fpga_0_RS232_RX_pin : IN std_logic;
    fpga_0_RS232_TX_pin : OUT std_logic;
    xps_gpio_0_GPIO IO I pin : IN std_logic_vector(31 downto 0);
    xps_gpio_0_GPIO IO O pin : OUT std_logic_vector(31 downto 0)
);)
end component;

component vsih_tv_g_v10 is
port(
    clk : in std_logic;
    rst : in std_logic;
    -- 1PPS and mode config
    one_pps : in std_logic;
    tvg_mode : in std_logic_vector (1 downto 0);
    pattern_ack : in std_logic;
    -- Output pattern
    pattern : out std_logic_vector (31 downto 0)
);
end component;

--The FX complex cross-correlator inside the Fila10G board consists of 5 blocks--
--Block 1: Input channel selection--
--Block 2: Delay--
--Block 3: FFT--
--Block 4: Complex multiplication--
--Block 5: Integration--

------------------------ Block 1: Input channel selection ------------------------

-- Inputs: the two channels selected by the user
-- Outputs: the sign and mag information for the channels

------------------------ Block 2: Delay ------------------------

-- Components delay_a and delay_b
-- Inputs: clk32M, valid_data, A/Bsign, A/Bmag from the channel selection
-- Outputs: A/Bsign_delayed, A/Bmag_delayed

------------------------ Block 3: FFT ------------------------

--20120814: Added the ':= 'X'' parts to the 512-bin FFTs

COMPONENT xfft_v7_512_1
port (  
    clk : in STD_LOGIC := 'X';
);
start : in STD_LOGIC := 'X';
fwd_inv : in STD_LOGIC := 'X';
fwd_inv_we : in STD_LOGIC := 'X';
rfd : out STD_LOGIC;
busy : out STD_LOGIC;
edone : out STD_LOGIC;
done : out STD_LOGIC;
dv : out STD_LOGIC;
xn_re : in STD_LOGIC_VECTOR ( 7 downto 0 );
xn_im : in STD_LOGIC_VECTOR ( 7 downto 0 );
xn_index : out STD_LOGIC_VECTOR ( 8 downto 0 );
xk_index : out STD_LOGIC_VECTOR ( 8 downto 0 );
xk_re : out STD_LOGIC_VECTOR ( 17 downto 0 );
xk_im : out STD_LOGIC_VECTOR ( 17 downto 0 );
);
END COMPONENT;

-- See also:
-- for LogiCORE IP FIFO Generator v8.1

-- Input signals in time domain with the delayed signals
-- Output signal in frequency domain
-- Output clock depends on the number of FFT bins

-- clk32M : in std_logic;

--Example like this:
--component FFT is
--port(
--   s1, s2 : in complex; -- inputs
--   phase_factor : in complex; -- phase factor
--   g1, g2 : in complex; outputs );
--end component;
--type complex is
--   record
--     r : real;
--     i : real;
--   end record;

--type comp_array is array (0 to 7) of complex;

--signal g1, g2: ... -- outputs
--constant phase_factor : ... -- phase factor
--...

----------------- Block 4: Complex multiplication -----------------
-- p = (a_real*b_real-a_imag*b_imag) + j(a_real*b_imag+a_imag*b_real)
-- See also: http://www.xilinx.com/support/documentation/ip_documentation/cmpy_ds291.pdf
-- For the Xilinx LogiCORE IP Complex Multiplier v3.1

-- Input from the two FFTs
-- FA* FB'
-- Output: correlated amplitude and phase

---------------------- Block 5: Integration ----------------------

-- Inputs are the outputs from the multipliers
-- Output: a mean of several results

-- Output: in numerical form
-- Output plots: amplitude and phase

--------------------------------------------------------------------------------
type data_buff is array(0 to 511) of std_logic_vector(25 downto 0);
type sig_mag is array(0 to 255) of std_logic_vector(2 downto 0);
type final_buff is array(0 to 511) of std_logic_vector(43 downto 0);

signal vsi_clk : std_logic;
signal clk_50m : std_logic;
signal proto_clk : std_logic;

signal tengbe0_tx_port : std_logic_vector(15 downto 0);
signal tengbe0_tx_ip : std_logic_vector(31 downto 0);
signal tx_data_pin : std_logic_vector(63 downto 0);
signal vsi1_data64 : std_logic_vector(63 downto 0);
signal vsi2_data64 : std_logic_vector(63 downto 0);
signal tx_discard_pin : std_logic := '0';
signal tengbe0_tx_eof : std_logic := '0';
signal tengbe0_tx_ack : std_logic := '0';
signal base_seconds : std_logic_vector(31 downto 0);
signal base_mjd_days : std_logic_vector(31 downto 0);
signal tengbe0_tx_valid : std_logic := '0';
signal data_mode_select : std_logic_vector(1 downto 0) := (others=>'0');

signal rx_data_pin : std_logic_vector(63 downto 0);
signal rx_valid_pin : std_logic;
signal rx_ack_pin : std_logic;
signal fake_onepps : std_logic :='0';
signal fake_onepps50 : std_logic :='0';
signal onepps : std_logic :='0';
signal onepps_1 : std_logic :='0';
signal rx_pps : std_logic :='0';
signal rx_valid : std_logic :='0';
signal seconds_counter : std_logic_vector(31 downto 0);
signal sample_counter : std_logic_vector(31 downto 0);
signal N : std_logic_vector(31 downto 0);
signal clk_200m : std_logic;
signal clk_150m : std_logic;
signal clk_100m : std_logic;
signal counter, counterm, counter2, counter2m : std_logic_vector(7 downto 0);
signal counter34 : std_logic_vector(33 downto 0);
signal tvg_pattern34 : std_logic_vector(33 downto 0);
signal counter68 : std_logic_vector(67 downto 0);

signal tengbe0_txdta : std_logic_vector(63 downto 0);
signal src_rd_en, src_full, src_empty,
full1,full2,full3,full4,empty1,empty2,empty3,empty4 : std_logic;
signal frame_counter : std_logic_vector(14 downto 0);
signal tvg_data68 : std_logic_vector(67 downto 0);
signal psn_counter : std_logic_vector(31 downto 0);
signal year : std_logic_vector(3 downto 0);
signal dbbc : std_logic_vector(11 downto 0);
signal test_vector,newclk : std_logic;
signal time_code : std_logic_vector(31 downto 0);
signal time_code_sec : std_logic_vector(19 downto 0);
signal time_code_days : std_logic_vector(11 downto 0);
signal rtc_arm : std_logic;
signal rtc_synced : std_logic := '0';

signal tvg_pattern : std_logic_vector(31 downto 0);
signal tvg_pattern_ack : std_logic := '0';
signal tvg_mode : std_logic_vector(1 downto 0) := (others=>'0');
signal tvg_mode_sysclk : std_logic_vector(1 downto 0) := (others=>'0');
signal tvg_mode_sysclk : std_logic_vector(1 downto 0) := (others=>'0');

--/* Interface Requirements signals */--

signal rst_global : std_logic ;
signal global_rst_sysclk, global_rst_sysclk1 : std_logic ;
signal station_id_pin : std_logic_vector(31 downto 0) ;
signal udp_dest_port_pin : std_logic_vector(31 downto 0) ;
signal udp_dest_ip_addr_pin : std_logic_vector(31 downto 0) ;
signal sys_stat_bits : std_logic_vector(31 downto 0) ;
signal sys_config_bits : std_logic_vector(31 downto 0) ;
signal years_2000 : std_logic_vector(31 downto 0) ;
signal mjd_days_current : std_logic_vector(31 downto 0) ;

--/* output format selection signals */--

-------------------------------------------------------------------

X"5C0000ABADC701CE";
signal frame_mk5b_data : std_logic_vector(63 downto 0) := (others=>'1');
signal frame_mk5c_data : std_logic_vector(63 downto 0) :=
X"FED1F0ABADC701CE";
signal frame_vdif_data : std_logic_vector(63 downto 0) :=
X"FED1F0ABADC701CE";
signal frame_mk5b_valid : std_logic := '0';
signal frame_mk5b_eof : std_logic := '0';
signal output_format_select : std_logic_vector(1 downto 0) := (others=>'0');

---------------------
-- Multiplexer I

----------------------------
signal tvg_data64: std_logic_vector(63 downto 0);
signal vsi22_data64: std_logic_vector(63 downto 0);
signal vsi11_data64: std_logic_vector(63 downto 0);
signal vsi12_data64: std_logic_vector(63 downto 0);

-- Multiplexer II

signal src_select: std_logic_vector(1 downto 0);
signal src_out68: std_logic_vector(67 downto 0);

--/* VSI11 data signals */--
signal vsi1_1_in : std_logic_vector(33 downto 0);
signal vsi2_1_in : std_logic_vector(33 downto 0);
signal vsi1_2_in : std_logic_vector(67 downto 0);
signal vsi12_1_in_data68 : std_logic_vector(67 downto 0);
signal vsi1_1_in_data68 : std_logic_vector(67 downto 0);
signal vsi2_1_in_data68 : std_logic_vector(67 downto 0);
signal vsi1_1_data64 : std_logic_vector(63 downto 0);
signal vsi1_onepps_in,vsi1_valid_in,vsi2_onepps_in,vsi2_valid_in : std_logic;
signal onepps_in,src_valid_in : std_logic;

signal from_myPC, to_myPC : std_logic_vector(31 downto 0);
signal mk5b_user_hdr_data : std_logic_vector(11 downto 0);

-- The additional signals for the correlator: channel selection, vsi data and sign/mag
-- for both channels

signal select_channel_A : std_logic_vector(3 downto 0);
signal select_channel_B : std_logic_vector(3 downto 0);
signal cha_A_user : integer range 0 to 15;
signal cha_B_user : integer range 0 to 15;
signal sig_mag_a : std_logic_vector(1 downto 0);
signal sig_mag_b : std_logic_vector(1 downto 0);
--
signal A_sig_mag : signed(2 downto 0);
--
signal B_sig_mag : signed(2 downto 0);
signal A_sig_mag : std_logic_vector(2 downto 0);
signal B_sig_mag : std_logic_vector(2 downto 0);
signal A_sig_mag_del, B_sig_mag_del : sig_mag;
signal vsi_data_in : std_logic_vector(63 downto 0);
signal vsi_data_in_A : std_logic_vector(31 downto 0);
signal vsi_data_in_B : std_logic_vector(31 downto 0);
signal A_sign, A_mag, B_sign, B_mag : std_logic;

-- Delayed signals
signal delayed_A, delayed_B : std_logic_vector(2 downto 0);
signal delayed_A_B, delayed_B_B : std_logic_vector(7 downto 0);
signal delay_A, delay_B : std_logic_vector(7 downto 0);

-- Constant d in the number of clock cycles by which the input should be delayed
constant d : integer := 100;
-- Signals for the FFT
  signal im_in_a, im_in_b : std_logic_vector(7 downto 0);
  signal xk_index_A, xk_index_B, xn_index_A, xn_index_B : std_logic_vector(8
downto 0);

-- Signals for the complex multiplication
  signal A_real, A_imag, B_real, B_imag : std_logic_vector(17 downto 0);
  signal multi_real, multi_imag : std_logic_vector(15 downto 0);

-- Signals for integration
  signal reset, data_enable : std_logic;
  signal data_real, data_imag : final_buff;
  signal buff_real, buff_imag : final_buff;
  signal sigma_real, sigma_imag : std_logic_vector(15 downto 0);

-- Input/Output files 20120529:
  file auto_file : text;
  file ch_input : text ;--open read_mode is "std_input";
  file ch_output : text ;--open write_mode is "std_output";
  signal frame : std_logic;

begin

myppc_system: myPC PORT MAP(
  fpga_0_rst_1_sys_rst_pin => '1',
  fpga_0_clk_1_sys_clk_pin => clk_50m,
  fpga_0_RS232_RX_pin => fpga_0_RS232_Uart_1_RX_pin,
  fpga_0_RS232_TX_pin => fpga_0_RS232_Uart_1_TX_pin,
  xps_gpio_0_GPIO_IO_I_pin => to_myPC,
  xps_gpio_0_GPIO_IO_O_pin => from_myPC );

to_myPC <= X"FFFFFFFE";

-- system clock from onboard 50MHz
clk_50m <= sys_clk_pin;

myclk_in : ibufds port map (i => vsi1_clkbuf_i_p,ib => vsi1_clkbuf_i_n,o => vsi_clk);

-- VSI INPUT

-- input from VSI1 In and VSI2 In, clocked in by VSI1 clock
  vsi1_in : for i in 0 to 63 generate
    vsi1_data64i : ibufds port map (i => vsi1_in_data64_p(i),ib => vsi1_in_data64_n(i), o =>
vsii1_data64(i));
  end generate;

  vsi_data_in_A <= vsi1_data64(31 downto 0);
vsi_data_in_B <= vsi1_data64(63 downto 32);

-- input validities and 1PPS'es
instvsi1pps: ibufds port map (i => vsi1_1pps_i_p, ib => vsi1_1pps_i_n, o =>
vsi1_onepps_in);
  instvsi1val: ibufds port map (i => vsi1_valid_i_p, ib => vsi1_valid_i_n, o => vsi1_valid_in);
instvsi2pps: ibufds port map (i => vsi2_1pps_i_p, ib => vsi2_1pps_i_n, o =>
vsi2_onepps_in);
  instvsi2val: ibufds port map (i => vsi2_valid_i_p, ib => vsi2_valid_i_n, o => vsi2_valid_in);
-----------------------------------------------------------------------------------------------
-- VSI OUTPUT
-----------------------------------------------------------------------------------------------

-- output to both VSI1 Out & VSI2 Out
myclk1_out : obufds port map (o => vsi1_clkbuf_o_p,ob => vsi1_clkbuf_o_n,i =>
vsi_clk);
  myclk2_out : obufds port map (o => vsi2_clkbuf_o_p,ob => vsi2_clkbuf_o_n,i =>
vsi_clk);

vsiout1: for i in 0 to 63 generate
  vsi1_data64op : obufds port map (o => vsi1_data64_o_p(i),ob => vsi1_data64_o_n(i), i =>
vsi1_data64o(i));
  end generate;
  instvsi1outval: obufds port map (o => vsi1_valid_o_p,ob => vsi1_valid_o_n,i =>
vsi1_valid_in);
  instvsi2outval: obufds port map (o => vsi2_valid_o_p,ob => vsi2_valid_o_n,i =>
vsi2_valid_in);
  instvsi1outppps: obufds port map (o => vsi1_1pps_o_p, ob => vsi1_1pps_o_n,i =>
vsi1_onepps_in);
  instvsi2outppps: obufds port map (o => vsi2_1pps_o_p, ob => vsi2_1pps_o_n,i =>
vsi2_onepps_in);

process
  variable index_3 : integer range 0 TO 511 := 0;
begin
  wait until rising_edge(vsi_clk);
  if (frame = '1') then
    index_3 := index_3 + 1;
  end if;
  vsi1_data64o <= data_real(index_3)(43 downto 12) & data_imag(index_3)(43 downto 12);
end process;

--------/* frame counter, 1 frame is 512 FFT bin */--------
process
  variable count125000 : integer range 0 TO 124999 := 0;
begin
  wait until rising_edge(vsi_clk);
  if (vsi1_onepps_in = '1') then
    count125000 := 0;
end process;
if count125000 = 0 then
    frame <= '0';
    count125000 := count125000 + 1;
else
    if count125000 = 124999 then
        frame <= '1';
        count125000 := 0;
    else
        frame <= '0';
        count125000 := count125000 + 1;
    end if;
end if;
end process;

---- Input channel selection for the cross-correlation ----

--Two processes to implement the selection of the sign/mag for both inputs

select_channel_A <= x"0"; -- variable to select the channel A as 0,1,2..F

process (vsi_clk, select_channel_A, vsi_data_in_A)

variable sel_a_int : integer range 0 to 15;
begin
    sel_a_int := conv_integer(unsigned(select_channel_A));
    if rising_edge(vsi_clk) then
        A_sign <= vsi_data_in_A(2*sel_a_int);
        A_mag <= vsi_data_in_A(2*sel_a_int+1);
        sig_mag_a <= A_sign & A_mag;
        case sig_mag_a is
            when "00" => A_sig_mag <= b"111";
            when "01" => A_sig_mag <= b"101";
            when "10" => A_sig_mag <= b"001";
            when "11" => A_sig_mag <= b"011";
            when others => null;
        end case;
    end if;
end process;

select_channel_B <= x"3"; -- variable to select the channel B as 0,1,2..F

process (vsi_clk, select_channel_B, vsi_data_in_B)

variable sel_b_int : integer range 0 to 15;
begin
    sel_b_int := conv_integer(unsigned(select_channel_B));
    if rising_edge(vsi_clk) then
        B_sign <= vsi_data_in_B(2*sel_b_int);
B_mag <= vsi_data_in_B(2*sel_b_int+1);
sig_mag_b <= B_sign & B_mag;
  case sig_mag_b is
    when "00" => B_sig_mag <= b"111";
    when "01" => B_sig_mag <= b"101";
    when "10" => B_sig_mag <= b"001";
    when "11" => B_sig_mag <= b"011";
    when others => null;
  end case;
end if;
end process;

-- select delay to apply to the stream A and B

delay_A <= x"00";
delay_B <= x"00";

process
  variable index_1: integer range 0 to 511;
  begin
    index_1 := conv_integer(unsigned(delay_A));
    wait until rising_edge(vsi_clk);
    A_sig_mag_del(0) <= A_sig_mag;
    for i in 1 to 255 loop
      A_sig_mag_del(i) <= A_sig_mag_del(i-1);
    end loop;
    delayed_A_8 <= A_sig_mag_del(index_1) & b"000000";
  end process;

process
  variable index_2: integer range 0 to 255;
  begin
    index_2 := conv_integer(unsigned(delay_B));
    wait until rising_edge(vsi_clk);
    B_sig_mag_del(0) <= B_sig_mag;
    for i in 1 to 255 loop
      B_sig_mag_del(i) <= B_sig_mag_del(i-1);
    end loop;
    delayed_B_8 <= B_sig_mag_del(index_2) & b"000000";
  end process;

---- FFT ----

-- 2 independent FFTs
-- BW is 32 MHz: with 512 points we get 256 frequency points
-- with 0.25 MHz each band
-- Target clock: 64 MHz
-- Data format: fixed point
-- Input data width: the minimum (8) was chosen and zeroes
-- put where not needed (we have 3-bit representation)
-- Phase factor: zero, minimum was 8 -> zeroed
-- Natural ordering

im_in_a <= x"00";
im_in_b <= x"00";

FFT_A : xfft_v7_512_1
PORT MAP ( 
  clk => vsi_clk, 
  start => '1', 
  fwd_inv => '0', 
  fwd_inv_we => '0', 
  rfd => open, 
  busy => open, 
  edone => open, 
  done => open, 
  dv => open, 
    xn_re => delayed_A_8, 
    xn_im => im_in_a, 
    xn_index => xn_index_A, 
    xk_index => xk_index_A, 
    xk_re => A_real, 
    xk_im => A_imag 
);

FFT_B : xfft_v7_512_1
PORT MAP ( 
  clk => vsi_clk, 
  start => '1', 
  fwd_inv => '0', 
  fwd_inv_we => '0', 
  rfd => open, 
  busy => open, 
  edone => open, 
  done => open, 
  dv => open, 
    xn_re => delayed_B_8, 
    xn_im => im_in_b, 
    xn_index => xn_index_B, 
    xk_index => xk_index_B, 
    xk_re => B_real, 
    xk_im => B_imag 
);

---- The complex multiplication and integration----

process (vsi_clk, A_real, A_imag, B_real, B_imag)
variable index: integer range 0 to 511;
begin
    index := conv_integer(unsigned(xk_index_A));
    if rising_edge(vsi_clk) then
        if vsi1_onepps_in = '1' then
            data_real <= buff_real;
            data_img <= buff_img;
        end if;
        multi_real <= A_real(17 downto 0)*B_real(17 downto 0) - A_imag(17 downto 0)*B_imag(17 downto 0);
        multi_img <= A_real(17 downto 0)*B_imag(17 downto 0) + A_imag(17 downto 0)*B_real(17 downto 0);
        buff_real(index) <= buff_real(index)+ multi_real;
        buff_img(index) <= buff_img(index)+ multi_img;
    end if;
end process;
end Behavioral;
In modern geodesy, space-related techniques play an important role. The three most significant of these techniques are the Global Navigation Satellite System (GNSS) that includes the Global Positioning System (GPS), the Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI). The next generation geodetic VLBI system, VLBI2010, covers everything from antennas to analysis and is being implemented at VLBI stations globally. One of the key requirements for VLBI2010 is the automation of the data analysis in order to reduce the latency of the results to 24 hours.

VLBI is a unique technique for determining the Earth Orientation Parameters (EOP), which are necessary, for example, when calculating satellite orbits. The accuracy of GNSS positioning is related to the accuracy of EOP. Therefore, it is important to measure these parameters with the best possible accuracy and as short latency as possible.