FGI PUBLICATIONS № 159

Finnish permanent GNSS network FinnRef

evolution towards a versatile positioning service

BY Hannu Koivula

NLS
FINNISH GEOSPATIAL
RESEARCH INSTITUTE
FGI

Aalto University publication series
DOCTORAL DISSERTATIONS 125/2019

Finnish permanent GNSS network FinnRef

evolution towards a versatile positioning service

Hannu Koivula

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall M1 of the school on 16 August 2019 at 12 noon.

This doctoral thesis is conducted in collaboration with Aalto University and Finnish Geospatial Research Institute.

Aalto University
School of Engineering
Department of the Built Environment

Finnish Geospatial Research Institute
Department of Geodesy and Geodynamics

Supervising professor
Professor Martin Vermeer, Aalto University, Finland

Thesis advisor
Professor Markku Poutanen, Finnish Geospatial Research Institute, Finland

Preliminary examiners
Professor Anna B. O. Jensen, KTH, Sweden
Assistant Professor Hans van der Marel, TU Delft, The Netherlands

Opponent
Professor Anna B. O. Jensen, KTH, Sweden

Aalto University publication series
DOCTORAL DISSERTATIONS 125/2019

ISBN 978-952-60-8629-3 (printed)
ISBN 978-952-60-8630-9 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8630-9

FGI Publications 159
ISBN 978-951-48-0261-4 (printed)
ISBN 978-951-48-0262-1(pdf)
ISSN 2342-7345 (print)
ISSN 2342-7353 (online)

Images: The cover image is from OLOS GNSS station in Lapland.
Copyright belongs to Simo Marila. Printed with permission.

Unigrafia Oy
Helsinki 2019

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Hannu Koivula

Name of the doctoral dissertation
Finnish permanent GNSS network FinnRef

Publisher School of Engineering

Unit Department of the Built Environment

Series Aalto University publication series DOCTORAL DISSERTATIONS 125/2019

Field of research Geoinformatics

Manuscript submitted 19 March 2019 **Date of the defence** 16 August 2019

Permission for public defence granted (date) 13 May 2019 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

The National Land Survey of Finland maintains the FinnRef network of continuously operating GNSS reference stations (CORS). FinnRef is the basis of the EUREF-FIN reference frame in Finland. Continuous time series ensure an accurate link between global GNSS-based coordinates and the national reference frame. In a CORS network it is essential that coordinates and coordinate time series of the reference stations are up to date, accurate and free from biases.

In this dissertation we introduce the development of FinnRef from a network of 13 GPS stations into a versatile modern positioning service. Both old and new FinnRef stations are explained and it is shown how a high quality CORS station should be established today. We were one of the first groups to show the annual periodicity of GNSS time series.

In Finland, land uplift is of high importance since it changes the coordinates continuously. We compared our uplift rates to independent results (tide gauges, precise levelling, GPS results of the BIFROST group). Agreement was very good showing that GPS is a powerful tool for monitoring the land uplift in Finland.

Using a baseline in Lithuania we tested an idea to validate GPS processing parameters against metrological ground truth. The length of the baseline is traceable to the definition of the metre with an uncertainty based on our calibrations. The test was successful and showed that for most accurate measurements individually calibrated antennas must be used.

After the first renewal phase of FinnRef we showed that our national network of 20 stations can provide NRTK corrections of the same accuracy level as services having five times more stations. The challenge was the reliability of individual coordinate measurements but this can be overcome by proper use of repeated measurements.

One of the most important results of this dissertation was that we showed the power of using metrological ground truth for validating GPS. The results of this dissertation will enable the creation of a dense GNSS based velocity field for intra-plate deformation models. This will improve the accuracy of transformations from measured GNSS coordinates to the national reference frame and make possible an accurate, reliable (semi)dynamic reference frame in Finland. It is also noteworthy that we showed how the FINPOS positioning service based on FinnRef data could give citizens direct access to the national EUREF-FIN reference frame. FinnRef could also be used as a backbone for GNSS corrections needed for intelligent traffic applications in Finland.

Keywords GNSS, FinnRef, FINPOS, time series, metrology, uncertainty, reference frame

ISBN (printed) 978-952-60-8629-3 **ISBN (pdf)** 978-952-60-8630-9

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2019

Pages 141 **urn** http://urn.fi/URN:ISBN:978-952-60-8630-9

A? **Aalto-yliopisto**

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Hannu Koivula

Väitöskirjan nimi
Finnish permanent GNSS network FinnRef

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Rakennetun ympäristön laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 125/2019

Tutkimusala Geoinformatiikka

Käsikirjoituksen pvm 19.03.2019 **Väitöspäivä** 16.08.2019

Väittelyluvan myöntämispäivä 13.05.2019 **Kieli** Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

Tiivistelmä

Maanmittauslaitos kerää satelliittipaikannusjärjestelmien (GNSS) lähettämää dataa jatkuvasti rekisteröivien FinnRef-tukiasemien avulla. Maanlaajuinen FinnRef-verkko on Suomen EUREF-FIN -vertauskehyksen runko. Verkon keräämät pitkät aikasarjat mahdollistavat tarkkojen muunnosmallien johtamisen satelliittipaikannusjärjestelmien tuottamien maailmanlaajuisten koordinaattien ja kansallisen EUREF-FIN -järjestelmän välille. On oleellista, että pysyvien GNSS-asemien tuottamat koordinaatit ja koordinaattien aikasarjat ovat laadukkaita ja virheettömiä.

Tässä väitöskirjassa esitetään Suomen pysyvän GNSS-verkon kehitys 13 aseman GPS-asemien verkosta kohti tiheämpää ja monipuolista paikannuspalvelua. Työssä esitellään alkuperäisen FinnRef-verkon ja uudistetun verkon rakenne, toimintaperiaatteet ja uusin tieto siitä kuinka asemat tulee tänä päivänä perustaa. Olimme yksi ensimmäisistä tutkimusryhmistä, jotka raportoivat GPS-aikasarjoissa selkeää vuotuista periodisuutta.

Suomessa eräs koordinaatteja jatkuvasti muuttava ilmiö on maankohoaminen. Vertasimme omia GPS:llä saatuja maankohoamisarvoja riippumattomiin tuloksiin (toistetut tarkkavaaitukset, mareografihavainnot ja kansainvälisen BIFROST-tutkimusryhmän eri metodilla tekemä GPS-analyysi). Yhteensopivuus oli hyvä ja osoitti GPS:n olevan tehokas työkalu myös maankuoren pystyliikkeiden seurantaan.

Testasimme Liettuassa olevalla perusviivalla mahdollisuutta validoida GPS-laskentaparametreja metrologisesti luotettavaan referenssimittaukseen. Mittauksen epävarmuusketju on tekemämme kalibroinnin perusteella jäljitettävissä metrin määritelmään. Testi osoittautui menestykselliseksi ja osoitimme, että tarkimpiin mahdollisiin mittauksiin jokainen GPS-antenni tulee kalibroida yksilönä.

Ensimmäisen FinnRef-verkon uudistuksen jälkeen osoitimme, että valtakunnallisella 20 tukiaseman GNSS verkolla voidaan päästä samalle tarkkuustasolle kuin viisi kertaa enemmän asemia olevissa palveluissa. Haasteeksi tulee yksittäisten mittausten luotettavuus, joka voidaan ratkaista toistomittauksin.

Väitöskirjan tärkeimpiä tuloksia oli osoittaa metrologisen lähestymistavan hyväksikäytön hyödyllisyys validoitaessa GNSS-laskentaparametreja. Tulokset mahdollistavat entistä tarkemman GNSS-tukiasemien dataan perustuvan maankuoren liikemallien luomisen, joka tarkentaa kansainvälisten ja kansallisen koordinaattijärjestelmien välistä muunnosta sekä aikariippuvan koordinaattijärjestelmän. Osoitimme myös, kuinka FinnRef-verkkoon perustuva FINPOS-paikannuspalvelu mahdollistaisi kansalaisille saumattoman pääsyn kansalliseen EUREF-FIN -järjestelmään. FinnRef-verkkoa voitaisiin hyödyntää myös runkoverkkona, joka voi osaltaan auttaa parantamaan älyliikenteen paikannuksen tarkkuutta.

Avainsanat Satelliittipaikannus, FinnRef, FINPOS, aikasarjat, metrologia, epävarmuus, vertauskehys

ISBN (painettu) 978-952-60-8629-3 **ISBN (pdf)** 978-952-60-8630-9

ISSN (painettu) 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2019

Sivumäärä 141 **urn** http://urn.fi/URN:ISBN:978-952-60-8630-9

Acknowledgements

This study was initiated at the Finnish Geodetic Institute, FGI, and completed at the Finnish Geospatial Research Institute FGI of the National Land Survey. I am grateful for a numerous people helping me to be a part of a researchers' family in Geosciences. The Directors General of the FGI during my research career, i.e., Prof. Juhani Kakkuri, Prof. Risto Kuittinen and Prof. Jarkko Koskinen as well as the Heads of the Department of Geodesy and Geodynamics Prof. Martin Vermeer and Prof. Markku Poutanen created an environment where research and legal responsibilities could be combined. Dr. Matti Paunonen and Dr. Matti Ollikainen introduced me to the world of space geodesy and reference frames. Also every single co-author of the publications included and excluded to this work are highly acknowledged as well.

Every single employee at the FGI are highly acknowledged. I have enjoyed all the research and non-scientific discussion with you in the corridors, at coffee tables, in pubs etc. These moments give me the fuel necessary to keep going.

The first touch of an international research environment I got as a young scientist being a part of BIFROST community. A memorable kick-off meeting took place in Onsala Space Observatory near Gothenburg, where a local delicacy called "surströmming" was served. Our colleague Pedro Elósegui (now in MIT, Haystack) was brave enough to taste this smelly fish for a photo opportunity … but the camera never worked. Pedro, I hope you enjoyed the fish. The rest of us didn't really enjoy the smell and we were served crayfish instead.

Things changed when Prof. Jarkko Koskinen, Kossu, become the head of the institute. You really pushed me to finish this work. My supervisor and instructors Prof. Markku Poutanen and Prof. Martin Vermeer also were there when they noticed that I was really going to finish this work. Dr. Pekka Belt gave me excellent tips on writing the compiling part of an article dissertation.

My research group needs a special acknowledgement as well. I really let you work on your own when I was concentrating on this work. You all were very supportive and understanding. Thank you for that.

Finally the support from my family was essential. My wife Mirjam gave me time to work in silence writing this thesis. My son Tino was also highly supportive and hardly complained when I made his play room into a home office. He also pushed me to finish this by continuously asking when he gets his room back.

Espoo, March 12, 2019
Hannu Koivula

Contents

List of Abbreviations

ADSL	Asymmetric Digital Subscriber Line, technology for data communication
AO	Allen Osbourne
ARP	Antenna Reference Point
ATX	Antenna Exchange Format
BeiDou	北斗卫星导航系统, Chinese Navigation Satellite System
BIFROST	Baseline Inferences for Fennoscandian Rebound, Sea-level, and Tectonics
BIPM	*Bureau international des poids et mesures*, The International Bureau of Weights and Measures
BTRF	BeiDou Terrestrial Reference Frame
CMR	Compact Measurement Record
CODE	Centre for Orbit Determination in Europe (Berne CH)
CORS	Continuously Operating Reference Station
DD	Double Difference
DGNSS	Differential GNSS
Doris	Doppler Orbitography and Radiopositioning Integrated by Satellite
DUTD	Delft University of Technology Design, conical radome for choke ring antennas
EAR	Elevation and Azimuth dependent non-differenced ionospheric free signal Residuals
ECEF	Earth-Centered Earth-Fixed
EDM	Electronic Distance Measurement
EOP	Earth Orientation Parameters
EMRP	European Metrology Research Program

EPN	EUREF Permanent GNSS Network
ETRF	European Terrestrial Reference Frame
ETRS	European Terrestrial Reference System
ETRS89	European Terrestrial Reference System 1989
EUREF	IAG Reference Frame Sub-Commission for Europe, IAG SC1.3a
EUREF-FIN	National ETRS89 realization of Finland
FGI	Finnish Geodetic Institute / Finnish Geospatial Research Institute
FINPOS	Positioning service of the NLS utilizing FinnRef data
FKP	FlächenKorrekturParameter, Areal Correction Parameter
GIA	Glacial Isostatic Adjustment
GLONASS	Глобальная навигационная спутниковая система, Russian Global Positioning System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRS80	Geodetic Reference System 1980
GSA	European Global Navigation Satellite System Agency
GTRF	Galileo Terrestrial Reference Frame
IAG	International Association of Geodesy
IERS	International Earth Rotation and Reference Systems Service
IfE	Institut für Erdmessung (IfE), Universität Hannover
IGS	International GNSS Service
INSPIRE	*Infrastructure for Spatial Information in Europe*. Directive for creating a European Union spatial data infrastructure
ISO	International Organization for Standardization
ITRF	International Terrestrial Reference Frame
ITRFyy	International Terrestrial Reference Frame, yy refers to the year of the realization
ITRS	International Terrestrial Reference System
MIT	Massachusetts Institute of Technology
N2000	Height system of Finland 2000
N60	Height system of Finland 1960
NGA	National Geospatial Intelligence Agency

NLS	National Land Survey of Finland
NRTK	Network RTK
MAC	Master-Auxiliary Concept
MAX	Master-Auxiliary Corrections
NKG	Nordic Geodetic Commission
PCC	Phase Center Correction
PCO	Phase Center Offset
PCV	Phase Center Variation
PPP	Precise Point Positioning
PRS	Pseudo Reference Station
PZ-90	Parameters of the Earth 1990, Reference Frame of Glonass
QIF	Quasi Ionosphere Free
RINEX	Receiver Independent Exchange Format
RTK	Real Time Kinematic
SCIGN	Southern California Integrated GPS Network
SCIS	A radome type for choke ring antennas designed at SCIGN. The last letter S indicates that SCIS is a short version of the SCIGN radome.
SLR	Satellite Laser Ranging
SNOW	Conical antenna dome for Ashtech choke ring antennas
SPP	Single Point Positioning
UPINLBS	Ubiquitous Positioning, Indoor Navigation and Location-Based Services
USAF	US Air Force
VLBI	Very Long Baseline Interferometry
VRS	Virtual Reference Station
WGS84	World Geodetic System 1984

List of Publications

This doctoral dissertation consists of a summary and the following publications which are referred in the text as Publication 1-6. All publications are peer reviewed.

Publication 1: Johansson J.M., J.L. Davis, H.-G. Scherneck, G.A. Milne, M. Vermeer, J.X. Mitrovica, R.A. Bennett, M. Ekman, G. Elgered, P. Elósegui, H. Koivula, M. Poutanen, B.O. Rönnäng, and I.I. Shapiro (2002). Continuous GPS measurements of postglacial adjustment in Fennoscandia, 1. Geodetic results. *Journal of Geophysical Research*. 107, B8, 2157, doi:10.1029/2001JB000400.

Publication 2: Poutanen M., H. Koivula, M. Ollikainen (2002). On periodicity of GPS time series. Vistas for geodesy in the New Millennium. Ed. J. Adam and K.P. Schwarz. International Association of Geodesy Symposia vol. 125, 388-392, Springer-Verlag.

Publication 3: Mäkinen, J., H. Koivula, M. Poutanen ja V. Saaranen, (2003). Vertical Velocities in Finland from Permanent GPS Networks and from Repeated Precise Levelling. *Journal of Geodynamics*, Vol 35, No.4-5, pp. 443-456.

Publication 4: Koivula, H., P. Häkli, J. Jokela, A. Buga, R. Putrimas (2012). GPS metrology – bringing traceable scale to local crustal deformation network. In S. Kenyon et al. (eds.), Geodesy for Planet Earth, International Association of Geodesy Symposia 136, Part 1, 105-112. DOI 10.1007/978-3-642-20338-1_13, Springer-Verlag Berlin Heidelberg 2012.

Publication 5: Koivula, H., Kuokkanen, J., Marila, S., Tenhunen, T., Häkli, P., Kallio, U., Nyberg, S. and M. Poutanen (2012). Finnish Permanent GNSS Network. Proceedings of the 2nd International Conference and Exhibition on Ubiquitous Positioning, Indoor Navigation and Location-Based Service (UPINLBS 2012), 3–4 October 2012, Helsinki, Finland. IEEE Catalog Number: CFP1252K-ART. ISBN: 978-1-4673-1909-6.

Publication 6: Koivula, H., J. Kuokkanen, S. Marila, S. Lahtinen, T. Mattila, (2018). Assessment of sparse GNSS Network for Network RTK. *Journal of Geodetic Sciences* Volume 8, Issue 1, Pages 136–144, ISSN (Online) 2081-9943, DOI: https://doi.org/10.1515/jogs-2018-0014.

Author's Contribution

Publication 1: This article reports on the work of the BIFROST (Baseline Inferences for Fennoscandian Rebound, Sea-level, and Tectonics) project. The analysis was done mainly by the first author, with contributions by the second and third authors. The author participated in the design and construction of the FinnRef stations and data transfer and was responsible for the data quality from the FinnRef sites as well as writing the description of the FinnRef sites.

Publication 2: The author did the processing of the GNSS data and did the periodicity analysis using Lomb periodograms. The third author did the power spectral analysis. The publication was written together with all authors and presented at the symposium by the first author.

Publication 3: The author was responsible for the data quality of the FinnRef stations and analysed all the GNSS data and performed time series analysis of them. The initial comparisons with BIFROST, levelling and tide gauge data were done by the author. The final results were compiled together with the first author. The publication was written together with the first author.

Publication 4: The author did all GNSS processing and comparison to the ground truth. The second and third authors contributed material on metrological traceability. The first author wrote the publication.

Publication 5: The author was leading the project in which the Finnish Permanent GNSS Network was upgraded, and wrote the publication. The other authors all belonged to the project team.

Publication 6: The research idea and analysis methods originate from the first author. The second, third and fourth authors did the field work. The second author prepared the publication together with the author. The author finalized the publication.

Summary of Publications

Publication 1: The article introduces the network of continuoisly operating GPS stations built around the postglacial rebound area at Fennoscandia. In the article first geodetic results of BIFROST project are published and possible errors in them are discussed.

Publication 2: The article shows the first findings of the periodical behaviour of the FinnRef GNSS data time series.

Publication 3: The article concentrates on vertical movement in Finland due to the postglacial rebound. In the article, results of the FinnRef permanent GPS network are compared to the results of the repeated precise levellings, tide gauge records and BIFROST project as well utilizing the FinnRef network.

Publication 4: The article introduces a method of using traceable distance measurements for validating GPS based vector estimates. GPS data were analysed with different linear combinations, antenna calibration models, ionosphere models and cut-off angles. The results were compared to metrological ground truth and conclusions and recommendations were given.

Publication 5: The article describes the details of the new Finnish Permanent GNSS Network. In planning of the network all the information from publication 1 and other sources were taken into account.

Publication 6: The article introduces the network RTK functionality of the new FinnRef network where all antennas are high quality individually calibrated. FinnRef is a very sparse network compared to the networks of commercial service providers. The FinnRef NRTK was tested on a test field and results were compared to the ones from private network RTK providers.

1. Introduction

During the last decades Continuously Operating Reference Stations, CORS, which collect data from Global Navigation Satellite Systems have become an important part of the global, regional and local geodetic infrastructures.

GNSS covers multiple Satellite Navigation Systems including the US Global Positioning System GPS, Russian GLONASS, European Galileo and Chinese BeiDou. All systems have some similarities. They all have the space segment with a number of satellites transmitting signals for navigation, and the ground segment with reference stations and uplinks for monitoring the behaviour of the system and updating the system data like orbit information transmitted to users. The third segment is the user segment. The user community ranges from hikers to scientists. In this thesis we concentrate on GNSS and CORS on the national level for reference frames and for Network RTK applications in science and surveying.

The International Terrestrial Reference Frame is maintained using the global GNSS network (Altamimi et al., 2016) and further continental densifications like EUREF Permanent GNSS Network, EPN, to provide a uniform regional reference frame (EPN, 2019a; Bruyninx et al., 2012). On the national level, more dense networks are used to maintain national reference frames and to monitor local and regional deformations. At the same time the real-time usage has increased. Private companies are building networks of their own providing network RTK services.

In all CORS work it is essential that coordinates and coordinate time series are accurately referring to the true values and have no biases. We have seen numerous studies about the periodic, secular or sporadic behaviour of the time series, antenna related issues etc. (Poutanen et al., 2004, 2005; Penna et al., 2007), or antenna calibrations (Görres et al., 2006, Kallio et al., 2019).

Today, there are high expectations for autonomous vehicles (cars, ships and airplanes). All of these systems require usage of multiple navigation and positioning sources. One of them is naturally GNSS. An accuracy requirement of 10 cm has been set. In this environment the correctness of the reference frame in use and of the observations from CORS stations is crucial information. Any inaccuracies will leak into end users' position solution.

The expectations for the accuracy of positioning are getting all the time higher. The coordinates are easily obtainable both in national and global frames, and an accurate relation between these is required. This leads automatically to the importance of site selection for CORS stations providing the basis for reference frames as well as correction services for positioning. Any biases at CORS stations leak automatically into end users' solutions. Metrology can contribute a traceable ground truth when studying the biases. Also, the detailed documentation and quality of the CORS sites and especially antenna calibration are becoming more important.

1.1 Motivation and aim of the dissertation

In 1998 the Finnish Geodetic Institute FGI created the current national reference frame EUREF-FIN based on two GPS campaigns in 1996–1997 (Ollikainen et al., 2000a, 2000b) and using the permanent GPS network FinnRef, built in 1994–1996 (Publications 1 and 2). In 2013–2014 the network was upgraded to track all navigation satellite systems and the number of stations was increased from 13 to 20. When the FGI was merged into the National Land Survey of Finland (NLS) in 2015, the NLS continued to operate and maintain the FinnRef network (Publication 5).

The network is also used for monitoring deformations of the reference frame. For these purposes it is essential that the coordinates and the coordinate time series, used for transformation between reference frames, are correct and have as small as possible errors and biases (Publications 1–4). The National Land survey will also utilize the FinnRef network for network RTK for its internal use from 2020 on.

Finland is in a postglacial rebound area that distorts the reference frame and height system (Publication 3). We know from repeated precise levelling and tide gauge time series the effect on the height system. GNSS time series give a tool for 3D monitoring of crustal deformations. However, there are some differences in the outcome depending on the processing strategy or connection to the reference frame (Publication 3). Also some error models and biases need still a closer look.

CORS stations can further be used for offering a real-time differential GNSS service and RTK measurements, giving an easy access to the reference frame (Publication 6). The key element is to verify that the coordinates measured by the end users refer to the national reference frame without significant biases.

1.2 Objectives and research questions

Coordinates and time series, and services provided using the CORS network are of major concern. The major objective is to guarantee the best quality coordinates and coordinate time series from the FinnRef permanent GNSS network. Objectives have been divided in this thesis into four research questions.

Research questions

(1) How should a modern GNSS network (CORS network) be established and utilized in Finland?
(2) How does the land uplift and crustal deformation obtained from GPS time series relate to independent methods and a Nordic solution?
(3) Can we provide a ground truth for evaluating the GPS accuracy?
(4) How does a modern GNSS network provide access to a reference frame for users?

These research questions are answered with six publications (1–6). Figure 1 shows the connections among the publications, and together with table 1 it shows the connections among the publications and research questions. In Publication 1 the first regional CORS network, including FinnRef, covering the Fennoscandian land uplift area is introduced. Publication 1 also gives the first precise point positioning (PPP) GPS analysis results by the BIFROST group. In Publications 2 and 3 the (double difference) GPS analysis of FinnRef is introduced. Publication 2 shows the periodical effects found on time series and publication 3 compares the first FinnRef results to the BIFROST results (Publication 1) and the results from the repeated precise levelling and tide gauge time series in Finland. In Publication 4 is introduced a method of comparing GPS baseline results with metrologically traceable ground truth. This way, optimal GPS processing parameters can be validated against the true values. In Publication 5 the new FinnRef network is introduced. All knowledge from the existing network and information from Publications 1, 3 and 4 and other sources were considered when network was designed. In Publication 6 is shown how a high quality, well designed but sparse CORS network performs in Network RTK production. Results are compared with ground truth and with the results using two commercial networks.

Table 1. Relation between publications and research questions Q1-Q4).

Publication	Q1	Q2	Q3	Q4
#1 Johansson et. al., 2002	X	X		
#2 Poutanen et al., 2002	X	X		
#3 Mäkinen et al., 2003		X		
#4 Koivula et al., 2012			X	
#5 Koivula et al., 2012	X			
#6 Koivula et al., 2018				X

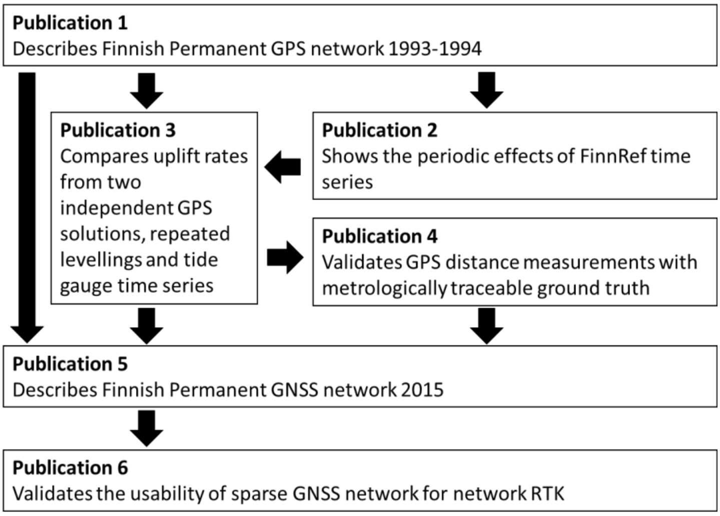

Figure 1. Relation of the Publications 1–6 and research questions.

1.3 Research process and dissertation structure

1.3.1 Finnish Permanent GNSS Network FinnRef

The author has been actively working with and was involved in all the actions related to the Finnish Permanent GNSS network FinnRef from the very beginning when the original network was designed and built in 1993–1996. During 2012–2013 the author was leading the project aimed at upgrading FinnRef from GPS only to a modern GNSS network, and making the final decisions on details related to the network. Currently, the author participates in a project group where FinnRef is further densified to fulfil NLS internal needs for network RTK.

The initial idea for the Fennoscandian Regional Permanent GPS network came from the directors of the Nordic Mapping Agencies and was proposed by the Nordic Geodetic Commission (Kakkuri et. al. 1995). In 1992 the Finnish Geodetic Institute decided to build a network of 12 GPS stations (Figure 2). The selection criteria for stations were (Chen and Kakkuri 1994):

(1) maximum land uplift difference can be detected,
(2) stations are on bedrock,
(3) absolute gravity can be measured at the station,
(4) there should be open sky above 15 degrees,
(5) stations can be easily connected to the precise levelling network,
(6) electricity and telecommunication should be accessible.

The site selection and mast designing work begun in the office and continued in the field. (Koivula et. al, 1999a), (Publication 1). The first masts were built in 1993 and the last station KUUS (Kuusamo) was installed in 1996. All sites except

SODA (Sodankylä) were built on bedrock. The first generation stations had three different types of masts for the antennas. A standard mast was a 2.5 meter height steel grid mast. The height of the mast was sufficient to mitigate the multipath of the ground reflections, but low enough that the thermal expansion of the mast during the yearly cycle was not significant. The annual height change is less than a millimetre. Three stations had concrete pillars, and higher masts at two stations had an invar stabilization system for height. (Paunonen, 1992)

On top of the steel grid mast there was a triangular plate that had a mounting hole for antennas on every corner, but only one mount place was ever used. Three different choke-ring type antennas were used (AOAD/M_B, AOAD/M_T and ASH700936A_M). Observations began with TurboRogue SNR-8100 receivers, but those were changed to Ashtech Z-XII receivers in 1995 due to reliability issues. The Ashtech antennas were covered with SNOW radome and the AOAD/M_T antennas with DUTD radomes. The METS (Metsähovi) and TUOR (Tuorla) stations did not have a radome.

The author tested the influence of radomes on coordinates in the early 1990's and concluded that it influences on height estimates as a small mm-level bias (only published in Finnish). This was considered to be acceptable compared to the situation where antennas are snow covered many months a year. Already in the beginning we decided not to change the setup, and especially not to touch the antenna mount in order to guarantee continuous uninterrupted time series.

The data with 30 s observing interval was collected to the FGI using a dial-up modem. In 2005 an ADSL (Asymmetric Digital Subscriber Line) connection was initialized and data collection was made hourly. The quality of the data was checked with the teqc program (Estey and Meertens, 1999). Mainly the number of epochs and multipath was monitored.

Three stations (METS, JOEN, VAAS and SODA) belong to the EPN network (EPN, 2019a) and METS belongs also to the IGS network (IGS, 2019). These connections enabled also a national realization of ETRS89, called EUREF-FIN that was created in 1998 (Ollikainen et al., 2000a and 2000b). In this work the author processed the data from the FinnRef based frame for densification.

In 2012–2013 the FGI upgraded the FinnRef network (Figure 2), Publication 5). All experiences from the old network as well as from other CORS operators were taken into account when the new network was designed. The first decision was that a completely new network will be built. New stations were built next to the old ones and several new locations were searched for as well. The main focus was to get better geographical coverage over Finland than the original FinnRef had. The connection between the old and new networks came via dual stations where the new mast and the receiver were installed alongside the old ones. The old and new networks were run in parallel until November 11, 2016 (i.e. 3-4 years of common operation). From that day on only the original EPN stations (METS, SODA, VAAS, JOEN) continued as dual stations.

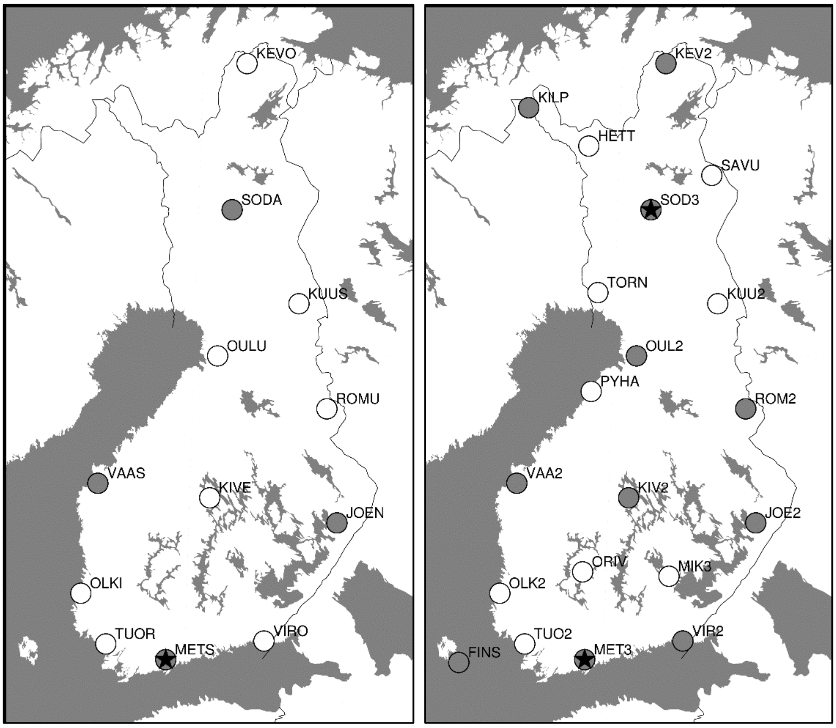

Figure 2. Original FinnRef network (left) and updated FinnRef network (right). Gray circles are EPN stations and stars also IGS stations.

A new antenna platform design was introduced, firstly so that snow will not accumulate on top of the mast, and secondly so that the new construction will cause less multipath. All antennas were individually calibrated and all had identical radomes. All stations have an identical construction.

1.3.2 GPS data and time series analysis of FinnRef network

In this chapter the data processing of publications 2 and 3 is explained. We used five years of FinnRef data, 1996–2001. We processed the data with the Bernese 4.0 software (Rothacher and Mervart, 1996) and created scripts that allowed fully automatic processing of the data. All FinnRef data were processed as 24 hour sessions using IGS precise orbit products. Baselines were created automatically and ambiguities solved baseline by baseline. In a final daily run an ionosphere-free linear combination of data was used and ambiguities were pre-eliminated keeping only METS fixed to its ITRF (International Terrestrial Reference Frame) coordinates. The normal equations were saved. The final coordinate solution for the FinnRef stations was a combination of a full GPS week where 7 days of normal equations were combined into one weekly solution. Time series of these weekly solutions are used for detecting velocities of the stations.

Very soon it was evident that the data had some periodic effects (Publication 2 and Poutanen et. al., 2004, 2005). For evaluating the periodicity of the data we used the Lomb periodogram (Press et al., 1996) since it allows unevenly sampled data like the FinnRef data with numerous gaps.

From the coordinate time series we solved for the velocity vectors of the sites relative to the fixed point (METS). The uplift rates were solved with three different methods. In the first method a robust regression (Huber, 1981) was used for linear trend fitting. In the second method also a sinusoid was solved and in the third method all the winter data between November and March were discarded. In the comparison to the uplift values from tide gauge records, repeated precise levelling and BIFROST solution, only the first method was used.

1.3.3 Validating GPS based distances in metrological sense

The FGI is the national standards laboratory for length. This gives us a unique opportunity to validate GPS related distance measurements to the metrologically defined traceable ground truth (Publication 4). In the publication, the other authors performed the scale transfer from Nummela Standard baseline to Kyviškės baseline using Electronic Distance Measurement (EDM) instruments, and computed the uncertainty of the transfer. They also did the GPS observations at the Kyviškės site. The Nummela Standard Baseline itself is not suitable for GNSS observations because it is in the forest and the pillars are under a small shelter. The present author did all the GPS processing and comparison to the metrological ground truth and wrote the publication.

The Kyviškės Baseline (Buga et al., 2008) has pillars on an open field. We collected 2 × 24 hours sessions of GPS data simultaneously from all pillars using geodetic dual frequency GPS receivers and choke ring antennas. All antennas were individually calibrated by Geo++.

The GPS analysis was done with Bernese software version 5.0 (Dach et al., 2007) using different processing options (table 2). All baselines were processed separately. The parameters changed were the ambiguity resolution strategy, cut-off angle, ionosphere model, and antenna calibration tables. We used relative and absolute antenna calibration tables from the IGS and also antenna specific tables by Geo++. For the ionosphere we used the global CODE model (University of Berne) and a local model created from our own data.

Baseline lengths with different processing parameters were then compared to the metrological ground truth and conclusions were made concerning optimum GNSS processing parameters.

Table 2. Different processing parameters tested for baseline length processing with Bernese Software.

Parameter	Values tested
cut-off angle	5°, 10°, 20°
Ionosphere model	Local (used 2-freq data from pillar 4) Global (CODE model)
Antenna calibration	Relative type calibration (IGS) Absolute type calibration Individual absolute (Geo++)
Ambiguity resolution	L1 (sigma dependent) L1&L2 (sigma dependent) narrow-lane QIF

1.3.4 Validating the sparse GNSS network for network RTK

In 2012 and 2013 the FinnRef network was upgraded with high quality equipment as described in Ch. 1.3.1. At the same time an open Differential GNSS, DGNSS, positioning service providing 0.5 m accuracy was released. In Publication 6 we investigated if this sparse FinnRef network (an average inter-station distance of 200 km) could be utilized for network RTK as well. De facto inter-station distances of 50–70 km are used by commercial service providers.

Our ground truth are the official coordinates of benchmarks selected for a test field. The test field was created so that the distance to the closest FinnRef station varies between 18.8 and 122.3 km. Also the positioning services by two commercial service providers in Finland were included in the test since they are offering the RTK services for their customers. Test were done using two different RTK receivers. The principles of the data analysis, performed with Matlab are described in Publication 6.

1.4 Structure of the dissertation

The summary of this dissertation comprises four chapters. The first chapter introduces the subject, gives the motivation to the research topics and introduces materials and methods. The second chapter gives the necessary theoretical background and the third chapter explains major findings. The fourth chapter is for discussion and recommendations for future research.

2. Theoretical foundation

2.1 Background

Continuously Operating Reference Stations (CORS) is a common name for all GNSS receiver/antenna combinations that are permanently installed and collect continuously data. There are several factors that can impact on the expected positioning accuracy of GNSS. These errors can be divided into satellite, medium, receiver and model based errors. Typical values for major GNSS positioning strategies are shown in Table 3 as shown in (GSA, 2018). The table has been updated by the author with information about Network RTK (NRTK) and CORS data processing. In the table 3 CORS PPP refers to a post processing solution when PPP is a real time solution. PPP requires an initialization time of 15 minutes or longer (Kouba et. al., 2017) before it converges to final accuracy level. This is a challenge in real time applications.

Table 3. Typical values for major GNSS positioning strategies as indicated in GSA, 2018. Methods marked with * has been added by the author. SPP refers to single point positioning, RTK to real time kinematic, NRTK to Network RTK, PPP to precise point positioning and DD to doube difference.

Method	Observable	Positioning	Frequencies	Horizontal accuracy	Coverage
SPP	Code	Absolute	SF/DF	5-10 m DF 10-30 m SF	Global
DGNSS	Code	Relative	SF	<1 to 5 m	100’s km’s
RTK	Carrier	Relative	DF	1 cm + 1 ppm	10’s km’s
*NRTK	Carrier	Relative	DF	2 cm	Areal
PPP	Code/Carrier	Absolute	DF	< 10 cm to 1 m	Global
*CORS PPP	Carrier	Absolute	DF	< 1 cm daily	Global
*CORS DD	Carrier	Relative	DF	< 1 cm daily	Global

2.2 Principle of Geodetic GNSS positioning

When the true distances to three satellites, the coordinates of which are accurately known in Earth-Centered Earth-Fixed (ECEF) reference frame, are known, we can determine our position (Figure 3). All GNSS satellites are transmitting microwave signals with frequencies between 1.2 and 1.6 GHz. The carrier waves are modulated with information that give access to time and thus allow the ranging. Navigation data is modulated on top of the code providing information like orbits of the satellites. (Hoffmann-Wellenhof et al. 2008)

All GNSS systems provide three different types of observables in several frequencies.

1. The pseudorange that is the signal propagation time from a satellite to the receiver scaled with the speed of light.
2. The carrier phase
3. The change in the signal frequency due to the Doppler effect between the receiver and the satellite.

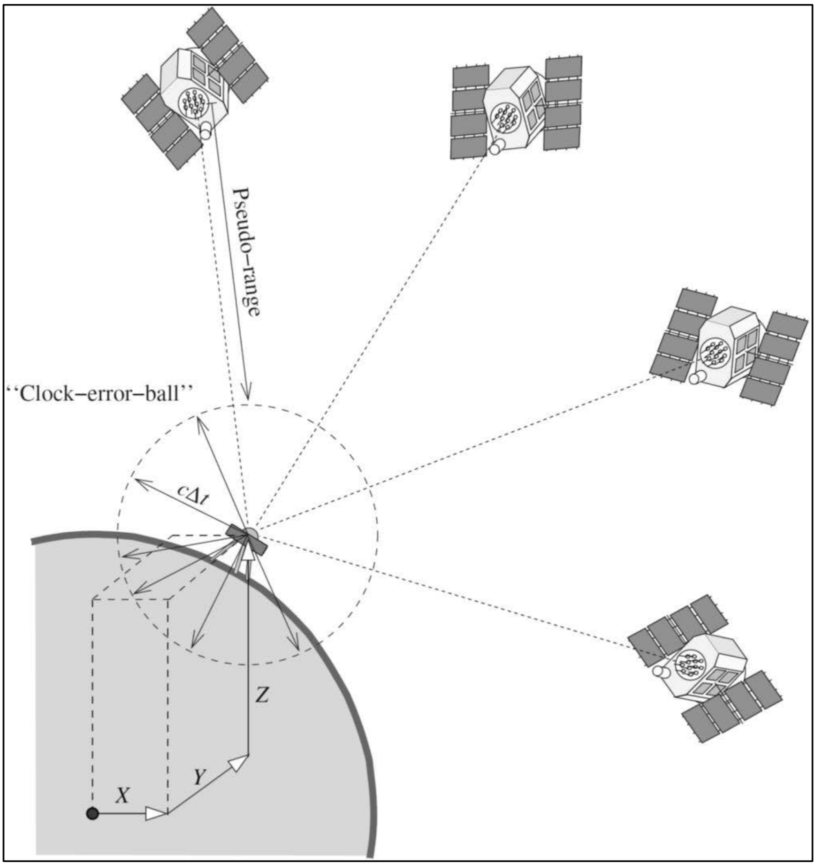

Figure 3. Principle of GNSS positioning. In an error free environment three accurate distance measurements from known orbits is enough for determining users' position. If the distance measurements are contaminated by an unknown receiver clock offset, one more satellite is needed. Other error sources may necessitate more satellites.

2.2.1 GNSS observables

The basic observable for GNSS positioning are pseudoranges (Hauschild, 2017). Code pseudo-ranges can be written as

$$p_{r,j}^{s}(t) = \rho_r^{s}(t) + \xi_{r,j}^{s}(t) + c\left(d_{r,j} - d_j^{s}\right) + c\left(dt_r(t) - dt^{s}(t) + dt^{rel}(t)\right) + I_{r,j}^{s}(t) + T_r^{s}(t) + e_{r,j}^{s}(t),$$

and the phase measurement in units of metre

$$\varphi_{r,j}^{s}(t) = \rho_r^{s}(t) + \xi_{r,j}^{s}(t) + c\left(\delta_{r,j} - \delta_j^{s}\right) + c\left(dt_r(t) - dt^{s}(t) + dt^{rel}(t)\right) - I_{r,j}^{s}(t) + T_r^{s}(t) + \lambda_j\left(\omega_r^{s}(t) + N_{r,j}^{s}\right) + e_{r,j}^{s}(t)$$

Where,

s	satellite
r	receiver
j	signal (L1, L2 etc.)
c	speed of light
t	time
$p_{r,j}^{s}$	pseudorange from satellite s to receiver r for signal j at time t
ρ_r^{s}	true distance
$\xi_{r,j}^{s}$	phase center offset of receiving and transmitting antenna
$\delta_{r,j}$	instrumental delay of receiver
δ_j^{s}	instrumental delay of satellite
$d_{r,j}$	receiver clock offset
d_j^{s}	satellite clock offset
dt^{rel}	relativistic correction
$I_{r,j}^{s}$	ionospheric delay (code delay or phase advancement)
T_r^{s}	tropospheric delay
λ_j	wavelength of frequency
ω_r^{s}	phase wind-up correction
$N_{r,j}^{s}$	integer ambiguity
$e_{r,j}^{s}$	noise

Superscript *s* refers to satellite, subscript *r* to receiver and *j* is the identifyer for the carrier frequency. In both cases we end up with a distance measurement as shown in a figures 3. In the case of carrier measurements also ambiguities need to be solved either to real or integer values. Ambiguities are the number of full wavelength cycles between a satellite and the receiver in the first epoch of the observation. As shown in the figure 4 and in previous equations the distance measurements are distorted by a number of errors and biases that have to be taken into consideration. Satellites are transmitting two or more frequencies allowing to minimize the effect of the ionosphere in measurements. This is based on the fact that the ionosphere is a dispersive medum at the frequencies of GNSS signals, so that group delays and phase advancement are frequency-dependent.

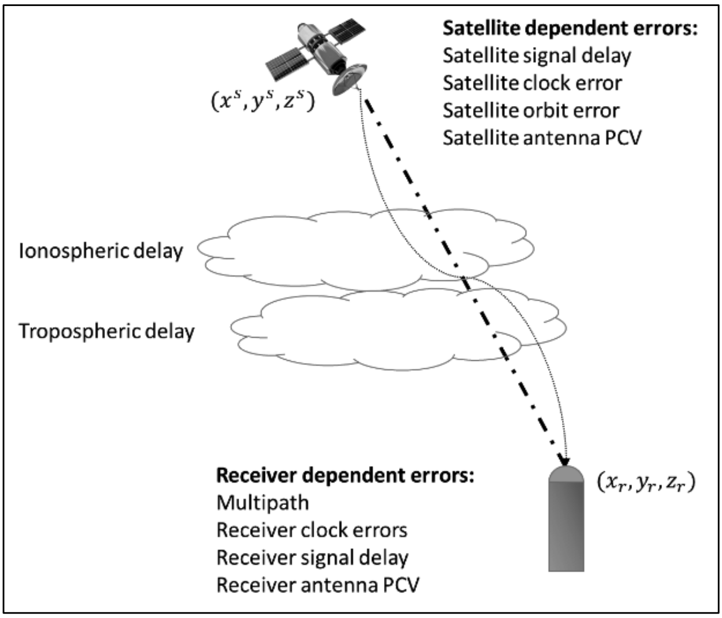

Figure 4. Pseudorange and error sources in GNSS observations.

The observed receiver coordinates are also affected by geophysical phenomena like the tidal deformation of the solid Earth. These are normally taken into account in the processing software.

2.2.2 Relative positioning

The most traditional way to deal with the error sources in surveying is using differencing of observables. It combines the data from a number of CORS stations. Typically, CORS stations data are stored with a 30 s observing interval. For coordinate maintenance purposes the observation sessions are typically 24 hours long. In the differential method the basic observables are differences between satellites and receivers (Fig. 5). The advantage of the approach is that it eliminates the residual clock error of satellite and receiver, and reduces atmospheric errors and orbit errors. Differencing increases the noise level of the observables. Also the results will be coordinate differences between CORS stations, which will however be more precise than any absolute coordinate solution for those stations could hope to be.

Figure 5 shows the most common differencing methods. Between satellites the single difference eliminates receiver related errors like the receiver clock. Between receivers the single difference eliminates satellite based errors like the satellite clock errors. The double difference combination of both single difference types eliminates both satellite and receiver errors. Also atmospheric errors are highly reduced if the receivers are close to each other. In triple differencing, that is a difference of double differences in consecutive epochs, also the integer ambiguity is eliminated, provided there are no loss-of-lock to the signal, i.e., cycle slips. The triple difference observable is mainly used for detecting cycle slips.

Differentiation does not eliminate all the biases. The satellite position has a different line of sight from all receivers. The effect of the bias on orbits of coordinates of the reference receiver is dependent on the baseline length between the receivers. When the broadcast ephemerides (of accuracy of 1 m) are used, the bias is estimated to be 0.05 ppm, and in the case of IGS precise ephemerides, 0.0025 ppm. This indicates 2.5 mm bias for a 1000 km baseline. Ionospheric delays are spatially correlated and therefore are highly reduced in the differencing process. (Odijk and Wanninger, 2017).

Differential receiver clock and hardware biases and differential ambiguities do not reduce or cancel out since they are not spatially correlated. They need to be estimated together with differential coordinates of the receivers. (Odijk and Wanninger, 2017).

There are still some biases that remain unmodelled. They are caused by ionospheric scintillation, multipath, radio interference, signal attenuation and diffraction. From these biases multipath is a dominant one. If a reference CORS station is affected by these biases their effect immediately leaks into the solution of other stations as well. For this reason special care has to be taken when selecting reference stations. (Odijk and Wanninger, 2017).

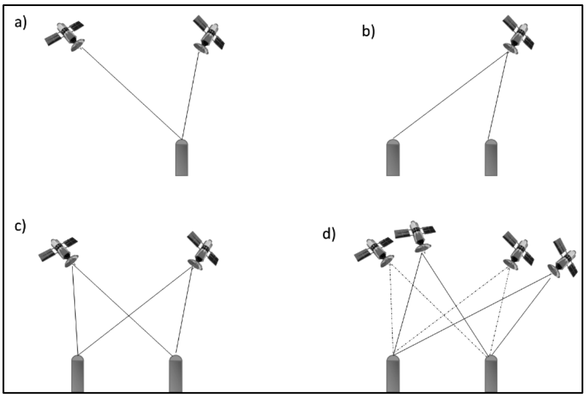

Figure 5. Differencing methods. a) between satellites single difference, b) between receivers single difference, c) double difference, d) triple difference

2.2.3 Precise Point Positioning

In precise point positioning the coordinates of a single CORS station can be derived directly in a global reference frame. The PPP model assumes globally consistent orbits and clocks that are provided by post processing of the global GNSS network and provided by, e.g., IGS. Therefore in PPP the orbits and clocks are considered fixed or heavily constrained. Since no differencing is done all the errors and biases affect the results in full power. Here we concentrate only on PPP of CORS stations. The most common case is to use dual frequency data and form the ionosphere free IF data combination that highly eliminates the ionospheric delay. The troposphere is a non-dispersive medium and therefore the tropospheric delay cannot be eliminated by using dual frequency observations. Total tropospheric delay tells how much the signal is delayed and it is divided into dry and wet parts. 90% of the delay is caused by the dry part and can be modelled. The wet part is caused by the atmospheric water vapour. In special cases the delay can be given as one number in the direction of the zenith together with a mapping function that gives refraction to any desired direction. Simplified equations for ionosphere free code pseudorange $p^s_{r,IF}$ and phase pseudoranges $\varphi^s_{r,IF}$ are (Odijk, 2017)

$$p^s_{r,IF} = \rho^s_r + c(dt_r - dt^s) + T^s_r + e_{IF}$$
$$\varphi^s_{r,IF} = \rho^s_r + c(dt_r - dt^s) + T^s_r + \lambda_{IF}A_{IF} + \varepsilon_{IF}$$

Where,

s	satellite
r	receiver
c	speed of light
t	time
$p^s_{r,IF}$	ionosphere free combination of pseudoranges p_A and p_B
$\varphi^s_{r,IF}$	ionosphere free combination of corresponding carrier phases
ρ^s_r	true distance
dt_r	receiver clock offset
dt^s	satellite clock offset
T^s_r	tropospheric delay
λ_{IF}	ionosphere free combination of the carrier-phase wavelengths
A_{IF}	noninteger ambiguity
ϵ_{IF}	measurement noise

For orbit and satellite clocks the precise products (like the IGS products) are used and considered known. For the “dry” part of the troposphere, i.e., the contribution of all constituent gases except water vapour, a model is applied. The “wet” part of the troposphere is described as the wet zenith tropospheric delay together with a mapping function. The unknowns for a typical PPP are coordinates of the station, receiver clock, zenith tropospheric delay and IF ambiguities.

2.2.4 Network RTK

Relative GNSS positioning can be done in real time when one receiver on a known location sends its data to the rover that solves the ambiguities (initialization) and the baseline between receivers. After initialization the measurements can continue in real time. This method is called the Real Time Kinematic (RTK) method and it is restricted to distances less than 30 km due to atmosphere and orbital errors.

When several base stations are networked, the distance dependency can be reduced. A network of CORS stations located typically 50–70 km from each other send their data in real time to a processing centre. The processing centre carries out station-wise error modelling and furthermore uses the data for constructing an areal error model. Corrections are then sent to the user, who can determine the position with the same accuracy as in non-networked RTK. This method is called Network RTK, NRTK. Network RTK is a powerful way to give users access to the reference frame.

Common ways to send data to the users are the RTCM and CMR formats. There are several different methods for determining corrections, VRS (Virtual Reference Station, Landau et al., 2002), FKP (FlächenKorrekturParameter, Wübbena, and Bagge, 2002), MAC (Master-Auxiliary Concept, Brown et al., 2006), MAX (Master-Auxiliary Corrections) and PRS (Pseudo Reference Stations) being most widely in use. The oldest and best known is the Virtual Reference Station, VRS, concept. There, the error model is used at the processing centre to generate virtual data to the user's position. The user is then performing RTK measurements with respect to the virtual reference station. In FKP also the error modelling is done at the processing centre and the coefficients of errors and data from one station are sent to the rover. In MAX the observations of the master station and differences to an auxiliary station are sent to the rover at same ambiguity level. The rover does the error modelling.

2.3 Reference systems and frames

The crust of the Earth is constantly moving and changing. All the points on the planet are moving due to plate tectonics, earthquakes and other phenomena deforming the crust. In order to accurately measure any coordinates we need an accurate reference system and its realization called the reference frame.

The coordinates of GNSS satellites, and thus the coordinates of the user, are in a global reference system. For practical purposes, the user may need a local coordinate system, which means that a coordinate transformation will be needed. In the following, both global and regional coordinate systems and their realizations in use are introduced.

2.3.1 ITRS and ITRF

The most important and conventional terrestrial reference systems is the International Terrestrial Reference System ITRS. The fundamental standards defining the ITRS are given in the Conventions of the International Earth Rotation and Reference Systems Service (IERS) (Petit and Luzum, 2010).

The global realization of ITRS is the International Terrestrial Reference Frame (ITRF). It is maintained by the International Earth Rotation and Reference Systems Service (IERS), an official service of the International Association of Geodesy (IAG). ITRF*yy*, with *yy* the year number of realization, is defined using the global networks of GNSS, SLR (Satellite Laser Ranging), VLBI (Very Long Baseline Interferometry) and DORIS stations. Since 1988 there have been 12 ITRFyy realizations, the latest one being ITRF2014 (Altamimi et al., 2016). Since the stations are located on different tectonic plates of the Earth, moving relative to each other, the coordinates realizing an ITRF*yy* are accompanied by epoch and velocity information.

IGS is a service of IAG that produces precise orbit products for most accurate needs. IGS orbit and clock products are commonly used in processing of the permanent GNSS station network. In scientific processing also the Earth Orientation Parameters (EOP) accompanying the precise orbits are applied. IGS orbits are given in ITRF*yy*, *yy* being the year of the realization.

2.3.2 WGS84

The Global Satellite Positioning System GPS is using the World Geodetic System 1984 (WGS84). (NGA, 2014). The realization of WGS84 is performed using DoD permanent monitoring stations. The coordinates of the stations are defined in ITRF*yy* and the epoch is given as a GPS week. The current WGS84 (G1762) agrees with ITRF2008 on GPS week 1762 and is accompanied with velocities as well. WGS84 (G1762) was realized through six GPS Control Stations by USAF (US Air Force) and 11 permanent stations by the National Geospatial Intelligence Agency (NGA), the coordinates of which were solved using IGS network data, coordinates and velocities as a reference. The latest realization has improved the consistency between ITRF and WGS84 since both IGS and NGA have adopted IERS Conventions 2010 methods and models in their data analysis (NGA, 2014).

Other GNSS systems, GLONASS, Galileo and BeiDou use their own reference frames, PZ-90 (Parameters of the Earth 1990), GTRF (Galileo Terrestrial Reference Frame) and BTRF (BeiDou Terrestrial Reference Frame), but they all are, like the WGS84, compatible with ITRF on the cm level.

2.3.3 ETRS, ETRF and EUREF-FIN

For practical purposes a time dependent reference frame has traditionally been considered unusable. EUREF, the subcommission of IAG, suggested that Europe should start using a system that is attached to the permanent part of the Eurasian tectonic plate. The system defined in that meeting is called European Terrestrial Reference System 1989 (ETRS89). The realization of the ETRS89 is maintained using EPN (EUREF Permanent GNSS Network) GNSS stations (Bruyninx et al., 2012). Currently there are 332 stations all over Europe, of which 20 are in Finland. The realizations of ETRS89 are called ETRF*yy*. The link between ETRS89, its realizations ETRF*yy* and ITRF are given in a EUREF memo (Boucher and Altamimi, 2011).

In Finland the national ETRS89 realization, ETRF96, is based on the coordinates of 100 first order benchmarks, measured by the GPS campaigns in 1996–1997, and of the 12 original FinnRef stations (Ollikainen et al., 2000a). EUREF-FIN is tied to the EPN through four EPN stations in FinnRef network. EUREF-FIN is the official reference frame of Finland identical to ETRF96 fulfilling the requirements of the INSPIRE directive. It is essential that the end users using, e.g., NRTK services will acquire proper EUREF-FIN coordinates.

2.3.4 Deformation of reference frames in Finland

As described in the previous chapter, the ETRS89 compatible reference frame in Finland is EUREF-FIN. The coordinates are ETRF96 coordinates that were realized in epoch 1997.0. The coordinates were corrected with plate tectonics to the epoch 1989.0. In Finland the Eurasian tectonic plate moves annually about 2.5 cm to the NE. The heights refer still to epoch 1997.0 because no land uplift models were applied in the transformation. The rigid motion of the tectonic plate can be taken into account using the method described in the memo by Boucher and Altamimi (2011). They give transformation parameters between ITRF and ETRS89 realizations as 14 parameters in total, 7 values and 7 time derivatives.

In addition to the rigid plate motion, there is the Glacial Isostatic Adjustment (GIA), the most notable effect of which is the postglacial rebound in the Fennoscandian area. This causes intra-plate motion as shown in Figure 6, showing the NKG RF03vel model by the Nordic Geodetic Commission (NKG) (Häkli et al., 2016). It shows that annual vertical velocities in Finland vary between 1 and 9 mm and horizontal velocities are up to 2 mm.

One way to improve the accuracy of transformations from ITRF to EUREF-FIN is to use GIA models and GNSS time series as described in Häkli et al., 2016.

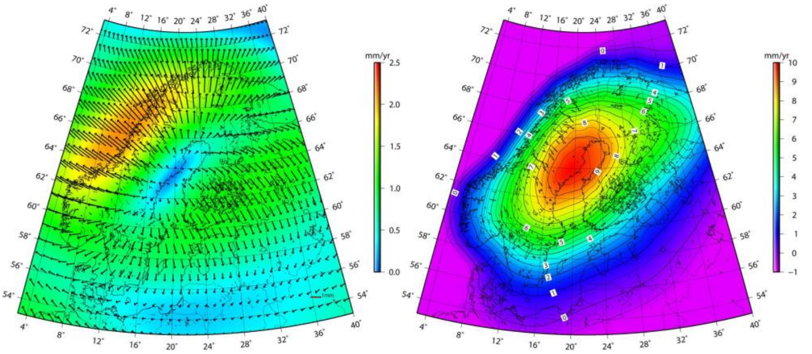

Figure 6. Intra-plate motion in caused by postglacial rebound according to the NKG RF03vel-velocity model.

2.3.5 Access to the reference frame

Nowadays the easiest access to the national reference frame is provided through Network RTK Services. In Finland we have two nation-wide commercial networks and one governmental for NLS internal use. By using the NRTK it is crucially important to be able to guarantee that the coordinates of the reference stations and especially the coordinates obtained using NRTK corrections refer to the national reference frame EUREF-FIN and do not have overly large errors or biases.

The Author participated in the work of the committee to create the Recommendations for Public Administration on measuring control markers in EUREF-FIN (JHS184, 2017). The Recommendation was created to guarantee the mutual compatibility and hierarchy of the measured coordinates. In the recommendation the coordinates are classified hierarchically into classes E1-E6 as traditionally has been done for centuries in surveying. The highest E1 class includes the FinnRef stations and the 100 benchmarks defining EUREF-FIN. The recommendation gives a possibility to measure lower order points (e.g. E4 or E5) using permanent GNSS stations having the E2 status. Any GNSS station can get official E2 status if rules given in (JHS184, 2017) are followed. Daily RINEX (Receiver Independent Exchange Format) files of the stations have to be sent to the FGI, who computes the official EUREF-FIN coordinates. FGI also monitors the quality of the stations continuously in order to guarantee that the coordinates given remain valid. If the station appears to be unstable, the validity of the E2 coordinates will be discontinued. JHS recommends that all stations that are used for providing NTRK corrections should be categorized into the E2 class.

2.4 Metrology

“Metrology is the science of measurement and its application. It includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.” “Metrological traceability is property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty”. (BIPM, 2012). The basic idea of metrology is to perform the measurement or calibration so that uncertainties with respect to the definition of the unit of interest can be verified.

2.4.1 Length Metrology at the FGI

The Finnish Geospatial Research Institute FGI-GG is a National Standards Laboratory of Length. Within this framework we calibrate electronic distance measurement (EDM) instruments and transfer the scale to geodetic baselines. In Finland, distance calibrations are mostly performed at the Nummela Standard Baseline. The FGI measurement standards for length is the Väisälä interference comparator with a quartz-gauge meter system. Baselines of 864 m and 432 m measured at Nummela with the Väisälä interference comparator have typically an extended uncertainty between 0.1 and 0.2 ppm (k=2). (Jokela, 2014).

The scale can be transferred from the Standard baseline to any other baseline using a measurement standard that is calibrated at the Standard baseline. The FGI uses as a measurement standard Kern Mekometer ME5000 or tacheometers which are calibrated at the Nummela Standard baseline. (Jokela et al., 2002). The uncertainty of the new baseline includes the uncertainties of the Standard baseline and of the scale transfer. (Jokela et al., 2002 and Publication 4).

2.5 GNSS antenna calibrations

GNSS antennas receive the signals transmitted by the GNSS satellites. Geodetic antennas have a physical antenna reference point (ARP) where the coordinates solved from observations should be referred to. This does not coincide with the electrical phase centre of an antenna seen by the actual signal. The electrical phase centre changes depending on the frequency of the received signal and the azimuth and elevation of its source. The electrical phase centre does not coincide either with the ARP, or with the physical centre of the antenna element. Antenna calibration gives a model for the offset between electrical phase centre and ARP.

The goal of antenna calibration is to map carrier phase based pseudorange observations from the satellites to the ARP. Figure 7 shows the relation between the average phase center, antenna reference point ARP, phase center offset (PCO) and phase center variation (PCV) for one signal. Calibration offers a phase centre correction PCC that is divided into phase centre offset and phase centre variation.

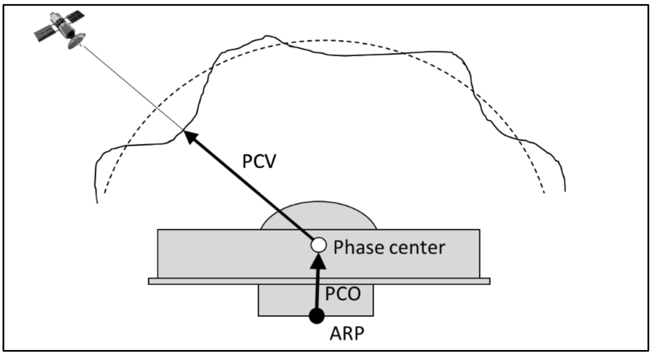

Figure 7. The principle of phase center correction PCC. The offset between antenna reference point ARP and average phase center is phase center offset, PCO. The correction associated with the direction to the satellite is called Phase Center variation, PCV. The ideal wave front around the phase center is shown as a dotted line.

Commercial software packages of receiver manufacturers have antenna models for at least their own antenna types. A uniform exchange format for antenna calibrations is the Antenna Exchange Format ATX that is commonly used at least in scientific data analysis. Figure 8 shows an example of an ATX file that shows the individual antenna calibration results of the MET3 antenna at the Metsähovi observatory. The calibration values are visualized in Figure 9. IGS maintains a list of institutions offering approved calibration services (IGS, 2018).

When a single antenna is calibrated it is called an individual calibration. When that value is expected to represent all antennas of the same type it is called a type calibration. It is also possible that type calibration values are determined by calibrating several antennas of the same type and a combination of them is then called a type calibration. Post processing software typically have type calibration values for different antenna types.

In the following, relative field calibration, absolute field calibration with a robot, and laboratory calibration in an anechoic chamber are described. Even if in the geodetic world the term "antenna calibration" is commonly used, it does not fulfil the definition of calibration in the metrological sense because the traceability chain and uncertainties to the definitions of SI units are not presented.

```
     1.4            M                                       ANTEX VERSION / SYST
A                                                           PCV TYPE / REFANT
created by: ant2atx May 01 2012 (c) 1998-2012 Geo++         COMMENT
run by: Geo++ GmbH, Garbsen/Germany                         COMMENT
                                                            END OF HEADER
                                                            START OF ANTENNA
JAVRINGANT_DM   SCIS00742                                   TYPE / SERIAL NO
ROBOT               Geo++ GmbH               1    2012-08-24METH / BY / # / DATE
     5.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     4                                                      # OF FREQUENCIES
FGI                                                         SINEX CODE
   G01                                                      START OF FREQUENCY
     +0.00      +1.01    +84.44                             NORTH / EAST / UP
   NOAZI   +0.00   -0.42   -1.61   -3.34   -5.32   -7.25   -8.89  -10.09  -10.72  ...
     0.0   +0.00   -0.36   -1.47   -3.13   -5.07   -7.00   -8.69   -9.95  -10.66  ...
     5.0   +0.00   -0.37   -1.48   -3.15   -5.08   -7.01   -8.70   -9.96  -10.68  ...
    10.0   +0.00   -0.37   -1.49   -3.16   -5.10   -7.03   -8.72   -9.99  -10.71  ...
    15.0   +0.00   -0.38   -1.51   -3.18   -5.13   -7.06   -8.75  -10.03  -10.75  ...
    20.0   +0.00   -0.38   -1.52   -3.20   -5.16   -7.10   -8.80  -10.08  -10.81  ...
```

Figure 8. Example of the antenna calibration ATX-file showing a beginning of the results for MET3 station.

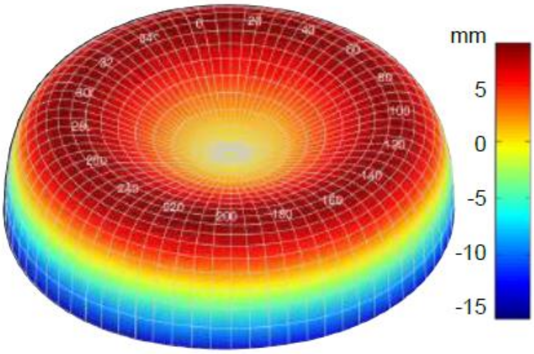

Figure 9. Visualization of the phase center variation, PCV. The PCV is very symmetric on high quality choke ring antennas. (Drawing U. Kallio)

2.5.1 Relative antenna calibration

In relative antenna calibration, observations were collected in the field over a short baseline and PCO and PCV were determined with respect to a reference antenna. The method was developed at the US National Geodetic Survey (Mader 1999). They used a short (5 m) baseline with fixed concrete piers with fixed antenna mounting planes. The reference antenna was on one pier and the antenna to be calibrated on the other pier. The reference antenna was always an AOAD/M_T choke ring antenna that was commonly used at IGS stations. The main ideology was that when the double differencing is used in processing and all antennas are calibrated with respect to the same antenna, the effect of the reference antenna cancels out in the differencing process. However, this is actually valid only for short baselines, when the change in horizon orientation due to curvature of the Earth and the change of satellite positions in the sky are negligible. In NGS they used the same type of receiver at both piers and both receivers were connected to the same rubidium oscillator. In the relative antenna calibration the PCO was determined as an average location of the phase centre and PCV had an elevation dependence only. (Hoffmann-Wellenhof et al., 2008)

2.5.2 Absolute antenna calibration

Geo++ and the Institut für Erdmessung (IfE), Universität Hannover developed a field calibration method that enables absolute antenna calibrations. Their method uses an accurately rotating and tilting robotic arm and allows to determine absolute PCO and PCV as a function of elevation and azimuth. They remove the effect of multipath by using differences of repeating satellite constellations. The antenna will be in a different position on the second observation day, otherwise also the PCV would cancel out. The automated robot takes thousands of observations with different orientations to detect PCV accurately. The PCV is then modelled using a spherical harmonic expansion as a function of azimuth and elevation and delivered to the users as an ATX file.

GNSS antennas can also be absolutely calibrated under laboratory conditions. The antenna is mounted on a robot arm allowing rotation and tilting, and installed in an anechoic chamber that absorbs the radio signal, making it a nearly multipath free environment. The signal source, a GNSS satellite emulator, transmits the signals with required frequencies allowing determination of PCO and PCV.

3. Results

In chapter 2 the research was divided into four research questions

(1) How should a modern GNSS network (CORS network) be established and utilized in Finland?
(2) How does the land uplift and crustal deformation obtained from GPS time series relate to independent methods and a Nordic solution?
(3) Can we provide a ground truth for evaluating GPS accuracy?
(4) How does a modern GNSS network provide access to a reference frame for users?

3.1 Research question 1: How should a modern GNSS network (CORS network) be established and utilized in Finland?

In this chapter we discuss how our understandings have changed over 20 years about constructing the highest order geodetic reference network. Most of that is related to technological development and increased accuracy, but part of it is due to new needs and applications.

Site selection criteria: *In the 1990*'s, in addition to the even coverage over the whole country, sites were selected to detect the maximum land uplift difference. Sites should also have open sky visibility above 15 degrees and be established on bedrock having a possibility for absolute gravity measurements. Stations should be easily connected to the precise levelling, electricity and telephone networks, and there should be a road to the site. The sites are in remote places and we had just a moderate protection against lightning.

Today we have basically the same criteria. The stability of the bedrock was confirmed using a relative gravimeter. A spring gravimeter is very sensitive to vibrations. We had two tests that a candidate antenna mast location had to pass. Firstly, the bedrock was hammered and it should have a minimum effect on the gravimeter reading. Secondly, the observer was changing his weight from one leg to the other causing the rock, if it would be a loose piece, to move a little. This would have been seen in the gravimeter reading. In the new stations, a special care has been taken to avoid problems with lightning. All equipment is connected to a common ground and we have 2–3 step protection on the electric power feed.

Antenna platform: *In the 1990's* we used several different mast types that were bolted to threaded rods cast with cement to drill holes in the bedrock. The standard mast was a 2.5 m steel grid mast that had a platform for 3 antennas on the top. The height change of that mast due to thermal expansion is less than 0.8 mm over the yearly cycle. Three of the sites were a part of a local deformation network. Those sites had 2 m height concrete pillars. Three sites had taller masts; Kevo (8 m), Oulu (8 m) and Metsähovi (25 m). The two latter ones had an invar stabilization system for height (Paunonen, 1992), which compensated the heights changes due to thermal expansion.

Today we use 3 meter high steel grid masts that are narrowed from the top to avoid the multipath that the older construction created (Figure 10). Also the new construction better prevents snow accumulating around the antenna. The antenna mounting hole and the corresponding bolt to fix the antenna are made according to the ISO 286-2 tolerances for holes and bolts. This allows us to remove and reinstall the antenna with high accuracy if it has to be taken down for a new calibration. The orientation of the antenna is secured by marking the North on the antenna platform.

GNSS receiver: *In the 1990's* the receiver had to be a dual-frequency GPS receiver that was listed in the IGS catalogue.

Today, the requirement is the same, but due to the technological development, the receiver must be able to track all navigation satellite systems and all civilian signals.

Figure 10. Old antenna mast (front) and new mast (behind) at the dual station Kevo. The old mast had a triangle shaped platform that caused multipath and the radome was conical. In the new construction the top of the mast is narrowed and the radome is spherical. Photo J. Näränen.

GNSS antenna. In the 1990's the Allen Osbourne (AO) Choke-Ring T type antenna was considered as a de facto standard for CORS stations. During the construction of the FinnRef stations, also Ashtech began providing similar antennas. We had a mixture of three slightly different Choke-Ring antenna types at the FinnRef stations, namely AOAD/M_B, AOAD/M_T and ASH700936AM.

Today, the choke ring antennas are still de facto standards, but there are several manufacturers. Antenna calibration has become more important, see below. All our new FinnRef stations are equipped with identical JAVRINGANT_DM Choke-Ring antennas.

Antenna Radome: There was a mixture of different radome types in use in the 1990's, but none of them were commercially available for AO D+M antennas. The University of Delft designed a conical radome made of glass fibre. We used those on some of the stations. On Ashtech choke ring antennas we used plastic conical SNOW radomes. The disadvantage with conical antennas was that the influence of the radome on the signal was not symmetrical around the phase centre of the antenna. This potentially can be seen as a bias or even as periodical behaviour when the constellation changes from day to day.

Today all the antennas are covered with spherical SCIS radomes.

Antenna Calibration: *In the 1990's* there were no individual antenna calibration values available. AO Choke Ring antennas were considered the best ones, and for them the antenna phase centre offsets from the ARP were available. The first Ashtech Choke Rings were considered identical to the AO choke rings. Other antenna types were calibrated with respect to the AO which was considered as the reference antenna. With increased accuracies this was no longer sufficient.

Today all antennas used in CORS stations are individually calibrated with radome on with azimuth and elevation dependence of the antenna phase centre.

3.2 Research question 2: How does the land uplift and crustal deformation obtained from GPS time series relate to independent methods and a Nordic solution?

Publications 2 and 3 had two major findings. We were one of the first to show that the GPS time series have significant annual periodic behaviour in all components (Koivula, 1999b, Koivula et al., 2002, Poutanen et al., 2004, 2005, Publication 3). This periodical effect has been later validated by all GNSS processing groups and studied further for example by Blewitt and Lavallée, 2002 and Penna et al., 2007.

Another important finding is the influence of the rime and snow accumulating on the antennas distorting the height solution (see Figure 12). During the first years of CORS stations in the 1990's, radomes were believed to solve the issue, but we showed that they do not solve the problem. During that time there were numerous ideas for solving this snow problem. People suggested heating elements, ventilators, rotating antennas etc. None of these really were taken into practice, mainly because of other issues they cause for antenna modelling or ice accumulation onto the radome. However, the snow tends to fall away from the radome as soon as the temperature rises above zero (Figure 11). This would not happen if radomes were not used. This is a main reason why in the high latitudes the radomes are still used even if they are not recommended by EPN.

Comparison between the uplift values from repeated precise levelling and a five year time series of FinnRef stations has an rms discrepancy of 0.6 mm/year. Comparison to other independent GPS analyses has actually a larger discrepancy, about 1 mm/year. This is partially due to a different processing strategy. In PPP the results are highly dependent on the reference frame and quality of the orbit products. Orbital products are dependent on the quality and stability of the CORS stations used in orbit generation. The differential approach is not so dependent on orbits. It generally gives better relative accuracy, but it is not clear that the results are correct in a global sense.

Our pioneering results showed that there is room for improvement especially when comparing different GPS processing strategies. Today the situation has improved when global coverage for high quality CORS stations is much better for orbit generation and reference frame realization. Also BIFROST GNSS time series are much longer. Lidberg et al., 2010, showed in their BIFROST solution that agreement between the PPP and double difference solutions agree on average at the 0.2 mm/year level.

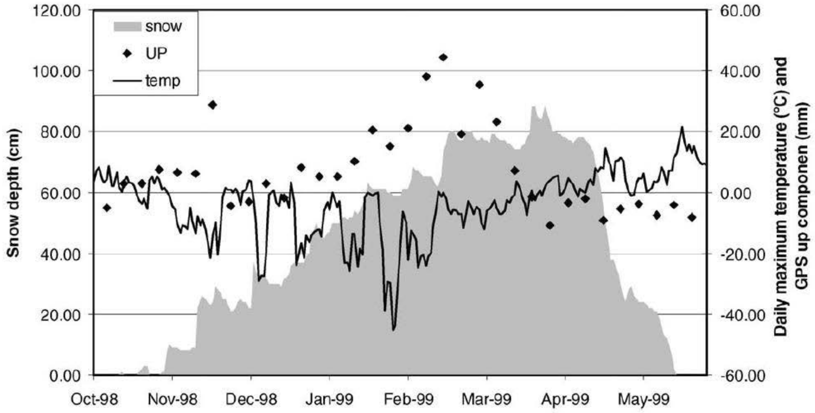

Figure 11. Relation between the height component of the FinnRef solution, temperature and snow depth (Publication 3).

Figure 12. FinnRef station at OLOS in western Lapland as an example how hard rime and snow accumulate on the antenna mast and antenna. (Photo S. Marila)

3.3 Research question 3: Can we provide a ground truth for evaluating GPS accuracy?

In Publication 4 we showed that it is possible to validate GPS results with respect to the metrologically traceable ground truth. By implementing this kind of approach, it is possible to evaluate how much different models and processing methods influence on the solution.

We used an EDM baseline in a deformation network 25 times and noticed some variation in the scale compared to GPS (Ahola et al., 2008). This led us to investigate the length measurements of GPS vs. traceable EDM measurements at the Kyviškės baseline in Lithuania. Kyviškės has ideal GPS observation conditions on an open field with distances ranging from 100 to 1320 m.

We showed in Publication 4 that even if high quality choke ring antennas are used, the largest uncertainty comes from using the ionosphere free linear combination of L1 and L2. Even if the uncertainties of L1 and L2 would be on the sub-millimeter level, the effect of constructing the ionosphere free L3 linear combination from them amplifies the effect. In our test this added up to a 4 mm difference in distance between antennas. This can be reduced to sub millimetre level when individually calibrated antennas are used (table 4). Therefore, individual antenna calibration is highly recommended when highest accuracy will be required.

It is feasible to measure an accurate ground truth for a small baseline or network. In our case the extended uncertainties (k=2) of scale transfer at Kyviškės baseline range from ±0.2 mm to ±0.9 mm. For a network of CORS stations separated by tens or hundreds of kilometres a traceable ground truth is nearly impossible to utilize. However, our findings that individual antenna calibrations minimize the uncertainties of the coordinate results can be utilized for CORS stations as well. There are number of projects where historic GNSS data from CORS stations are reprocessed due to improved models and methods, including individual antenna calibrations (EPN 2019b, Lahtinen et al., 2018).

The work in metrology has continued in the JRP SIB60 “Metrology for Long Distance Surveying” project (Pollinger et al., 2015), (Kallio et al., 2019).

Table 4. Statistic of GPS based distance measurements when compared to traceable ground truth. Both absolute type calibration and individual antenna calibration results are shown.

		L1 (mm)	L1&L2 (mm)	QIF (mm)
Absolute	Mean	-0.1	-0.1	0.0
	Min	-1.3	-0.7	-3.9
	Max	1.0	0.7	2.8
Individual	Mean	-0.1	-0.1	-0.1
	Min	-0.6	-0.5	-0.9
	Max	0.4	0.3	0.8

3.4 Research question 4: How does a modern GNSS network provide access to a reference frame for users?

The reference frame is defined typically by a national authority. Traditionally the access to the reference frame is provided through a set of benchmarks, the coordinates of which are in the national system, like EUREF-FIN in Finland. In RTK measurements these benchmarks are used as base stations. NRTK made it possible to perform measurements with a rover unit applying the NRTK corrections based on a network of CORS stations. EUREF-FIN benchmarks and CORS stations are classified into six accuracy classes (E1-E6), of which E1 is highest defining the system. E1 and E2 classes are the highest nation-wide coordinate classes and maintained by authorities like the NLS. NLS/FGI provides EUREF-FIN coordinates for the private NRTK stations if the provider follows the Recommendations for Public Administration and applies for E2 status for their CORS stations (JHS184, 2016). This ensures that the coordinates of the reference stations are defined in an official homogeneous way.

The FGI validated that commercial RTK services provide reliable data at the accuracy level they promise. At the time of the test, the Trimnet had official E2 coordinates (VRS) and the HxGN SmartNet did not (MAX), but unofficial E2 coordinates were provided for them.

Secondly we showed in our feasibility study that it is possible to achieve the same accuracy level with the FinnRef network using PRS corrections. FinnRef had only 1/5 of the number of stations compared to the commercial networks. Reducing the number of CORS stations decreases significantly the cost of building up a NRTK service. On the other hand we showed that even if it is possible to achieve a high accuracy level, a sparse CORS network also leads to increased false initializations at the rover end. This can only be overcome with a measurement procedure where several independent measurements are made using individual ambiguity initialization.

Table 5. The accuracy values of the tests show that the commercial NRTK networks provide reliable coordinates with better than 2.5 cm accuracy (rms) horizontally. The sparse FinnRef network was able to provide the same accuracy level using PRS corrections.

			All Obs		Ini Obs		Correct Ini Obs	
MP	Rec.	Network	H rms	V rms	H rms	V rms	H rms	V rms
MAX	GS14	Smartnet	0.028	0.052	0.028	0.052	0.023	0.048
VRS	R10	Trimnet	0.016	0.040	0.016	0.040	0.016	0.040
PRS	R10	NLS	0.028	0.060	0.028	0.060	0.022	0.056
PRS	R10	NLS (Ext)	0.045	0.103	0.045	0.103	0.027	0.095

4. Discussion

4.1 Theoretical and practical implications

An important theoretical result is the idea to use the metrologically traceable ground truth when validating GNSS processing parameters. This method enables us to validate models and parameters one by one against the real ground truth. We also showed in practice that this kind of approach can lead to recommendations that have a basis in metrology.

We were one of the first groups conducting this type of research and we have seen later that also other groups were taking GNSS metrology into their agenda. In recent years also the European Metrology Research Program (EMRP) has included GNSS metrology into their agenda. We participated in the JRP SIB60 "Metrology for Long Distance Surveying" project (Pollinger et al., 2015), (Kallio et al., 2019). The new project of the European Metrology program, called Geometre, is starting in mid-2019. In Geometre we undertake an effort to introduce metrology into the local tie measurements of geodetic core stations equipped with GNSS, SLR, VLBI etc. This will strengthen the reliability and accuracy of global reference frames in the future.

The new FinnRef, with nearly 50 stations in 2019 (Figure 13), will be the highest order network of the Finnish reference frame. The network is connected to the international IGS and EPN networks. We have used all the latest information to make it as reliable as possible and stable in the long term. Most of the stations are on bedrock and their stability is monitored. This dense reference network will offer us a possibility for an active definition of the reference frame. Active definition means that the national reference frame is defined by the permanent GNSS stations and the positioning service they offer instead of a number of fixed benchmarks.

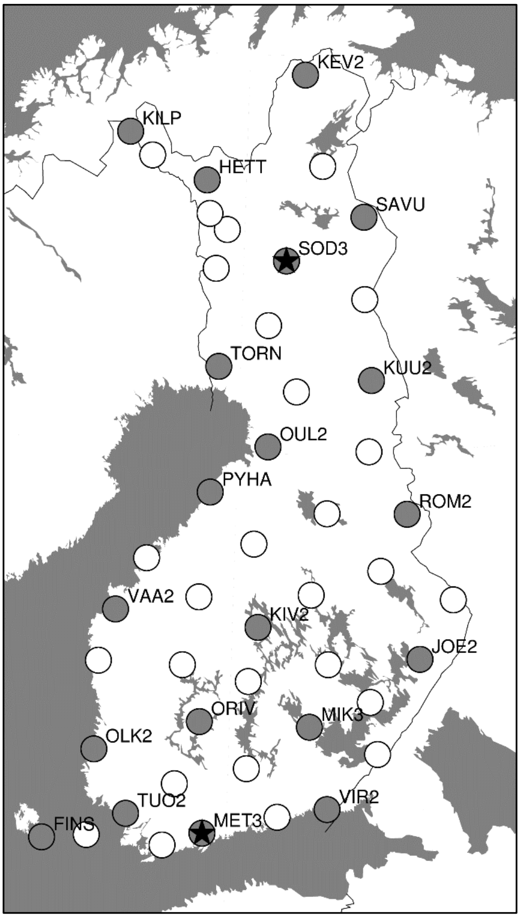

Figure 13. FinnRef network after the current dencification in 2019. White circles are new stations. Gray circles are EPN stations (20) and stars also IGS stations (2). FINPOS positioning service uses all stations.

Traditionally the national coordinate systems have been static and society has not been ready for time dependent coordinate systems. Today, and in the near future, precise point positioning (and the Galileo High Accuracy Service together with other global correction services) will become more common. This thesis verifies that the accuracy level of FinnRef is good and may in the future be used for a direct link between dynamic coordinates provided by PPP and the national reference system. Also we have a good reliable basis for discussion if semidynamic or dynamic reference frames should be utilized. In New Zealand the national Reference Frame NZGD2000 is already a semi-kinematic (Blick and Donelly, 2016). Our work has made it possible to:

1. Create a dense FinnRef based velocity field for intra-plate deformation models. This will improve the accuracy of transformations from measured GNSS coordinates to the national realization.
2. Define a (semi-)dynamic reference frame in Finland accurately and reliably.

This work shows that FinnRef can also be used successfully for network RTK in our official reference frame. Currently the National Land Survey is engaged in a project where FinnRef will be utilized and densified for the network RTK needs of NLS. In the planning, the other needs of public bodies and broader society are also under evaluation. We are for example creating a service that evaluates the quality of received GNSS signals and may be used for warning professionals and citizens in case of natural or human made disturbances in the GNSS signal or positioning results.

In 2018 the Parliament of Finland endorsed the "Report on Spatial Data Policy" (MMM, 2018). The report underlines the benefits of making precise positioning accessible for all. This thesis verifies that the FinnRef positioning service, FINPOS, would give a direct access to the reference frame. It can be used also as a backbone for GNSS corrections needed for intelligent traffic applications in Finland. As the first example FINPOS already offers positioning services at Lapland's Aurora Ecosystem for testing intelligent traffic in extreme weather conditions. The Aurora ecosystem is maintained by the Road Administration of Finland. The validity of the service is currently evaluated by the FGI under an ESA funded Arctic-PNT project.

4.2 Reliability and validity

As the National Standards Laboratory of Length we can verify the metrological ground truth for our GNSS metrology with a traceable uncertainty to the definition of the metre. Comparison to the traceable ground truth is a reliable way to test the processing parameters and methods. The method is expandable and recommendable for any testing purposes.

Our requirements for CORS stations are in line with recommendations by EPN and IGS. We have taken some steps further in stability and requirements for antenna mounts by not using buildings, but bedrock only. Certainly we are in a favourable position in Finland where a lot of bedrock is available. This recommendation is not valid everywhere in the world. Establishment of a long-term stable antenna mount would be much more demanding.

Our NRTK analysis software package GNSMART makes a continuous analysis of the phase residuals and creates elevation and azimuth dependent non-differenced ionospheric free signal residuals (EAR). Figure 14 shows the EAR of SOD2 station. Low residual indicate that our mast construction together with individually calibrated high quality choke ring antennas provide high quality data for both reference frames and NRTK production.The station is only slightly disturbed in very low elevations where vegetation is causing multipath.

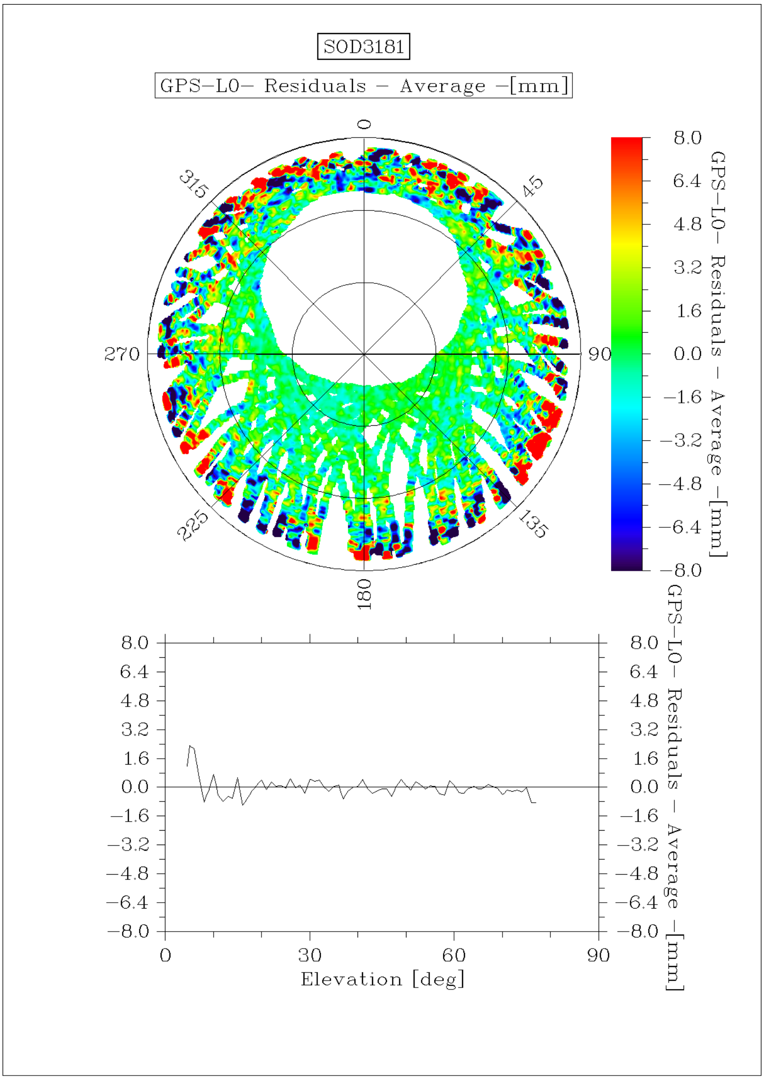

Figure 14. GPS L0 residuals of SOD3 station (see Figure 13 for location).

4.3 Recommendations for further research

From the metrological point of view, a true metrologically traceable 3D test field would give a possibility to test the uncertainties of GNSS processing parameters and models. In this thesis we used only distances. A new Geometre project by the European Metrology Research Program is a step in this direction. In the project we will define metrologically solid methods for defining local tie measurements at fundamental geodetic stations.

Most, if not all, current national reference frames created by GNSS are made using GPS only or GPS and Glonass data. An important research topic is to validate the results when Galileo and BeiDou are included into the process. The reference frame should be accurate and reliable with any combination of GNSS utilized by the end user.

The influence of GNSS antennas and their calibration at CORS stations should be studied. We have already shown in the GPS-only processing the importance of individual antenna calibrations. Most of the EPN sites have individual calibration values for GPS and possibly for Glonass. The impact of the upcoming GPS L5 and Galileo calibrations on GNSS processing and accuracy should be studied. However, it is unlikely that all European CORS antennas would be removed and re-calibrated for Galileo and BeiDou.

In the Arctic conditions it would be interesting to study if the antenna calibration values have a temperature dependency. Also the possible aging of radomes should be under investigation.

Antenna calibration alone is not enough since the whole surroundings of the antenna influences on the results as well. If one could find a traceable way to construct a time dependent site specific correction model for CORS stations as a whole that would give a high impact on geodesy.

Finally, as an answer to the “Report on Spatial Data Policy” accepted by Parliament, there should be a study on how an improved cost-free FinnRef and FINPOS would influence industrial development, innovations etc.

Bibliography

Ahola, J., Koivula, H., Poutanen, M., and Jokela, J, 2008. GPS Operations at Olkiluoto, Kivetty and Romuvaara in 2007. *Working Report* **2008-35**. Posiva Oy. 189 p.

Altamimi, Z., Rebischung, P., Metivier, L., and Collilieux, X., 2016. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *J Geophys Res Solid Earth*, **121**, https://doi.org/10.1002/2016JB013098

BIPM, 2012. International vocabulary of metrology – Basic and general concepts and associated terms (VIM), 3rd edition. *JCGM* **200:2012**. Joint Committee for Guides in Metrology.

Blick, G. and Donnelly, N., 2016. From static to dynamic datums: 150 years of geodetic datums in New Zealand. *New Zealand Journal of Geology and Geophysics*, **59** (1), pp. 15–21. DOI:10.1080/00288306.2015.1128451.

Blewitt, G., and Lavallée, D., 2002. Effect of annual signals on geodetic velocity. *Journal of Geophysical Research*, VOL. 107, NO. **B7**, 10.1029/2001JB000570, 2002.

Boucher, C., and Altamimi, Z., 2011. Memo: specifications for reference frame fixing in the analysis of a EUREF GPS campaign. Version 8: 18-05-2011

Brown, N., Geisler, I., and Troyer, L., 2006. RTK Rover Performance using the Master-Auxiliary Concept, *Journal of Global Positioning Systems* **5**(1-2):135-144.

Bruyninx, C., Habrich, H., Söhne, W., Kenyeres, A., Stangl, G., and Völksen, C., 2012. Enhancement of the EUREF Permanent Network Services and Products, "Geodesy for Planet Earth", *IAG Symposia Series*, Vol. **136**, pp. 27-35, DOI:10.1007/978-3-642-20338-1_4).

Buga, A., Jokela, J., and Putrimas, R., 2008. Traceability, stability and use of the Kyviškės calibration baseline – the first 10 years. In Cygas, D., and K. D. Froehner (Eds.): *The 7th International Conference Environmental Engineering, Selected Papers*, Vol. **3**, p. 1274-1280. Vilnius, Lithuania, May 22-23, 2008.

Chen, R., and Kakkuri, J., 1994. Feasibility study and technical proposal for long-term observations of bedrock stability with GPS. *Report YJT*-**94-02**. Nuclear Waste Commission of Finnish Power Companies. Helsinki. 33 pp.

Dach, R., Hugentobler, U., Fridez, P., and Meindl M., (Eds.), 2007. Bernese GPS Software Version 5.0. January 2007. Astronomical Institute, University of Bern.

EPN, 2019a. EUREF Permanent GNSS Network. http://www.epncb.oma.be, accessed 12.3.2019.

EPN, 2019b. EPN Repro2. http://epncb.oma.be/_productsservices/analysiscentres/repro2.php, accessed 24.5.2019

Estey, L., and Meertens, C., 1999. TEQC: The Multi-Purpose Toolkit for GPS/GLONASS Data. *GPS Solutions* Vol. **3**, No. **1**, pp. 42-49 (1999). https://doi.org/10.1007/PL00012778

GSA, 2018. *GNSS User Technilogy Report*, Issue **2**. doi: 10.2878/743965

Görres, B., Campbell, J., Becker, M., and Siemes, M., 2006. Absolute calibration of GPS antennas: laboratory results and comparison with field and robot techniques. *GPS Solutions* (2006) **10**: 136-145.

Hauschild, A., 2017. Basic Observation Equations, in: Teunissen P.J. and Montenbruck O. (eds), Springer Handbook of Global Navigation Satellite Systems, *Springer Handbooks*, Springer, Cham, 2017, 561-582.

Hofmann-Wellenhof, B., Lichtenegger, H., and Wasle, E., 2008. GNSS-global navigation satellite systems: GPS, GLONASS, Galileo, and more. Springer. ISBN 978-3-211-73012-6.

Huber, P., 1981. Robust Statistics. Wiley, New York.

Häkli, P., Lidberg, M., Jivall, L., Nørbech, T., Tangen, O., Weber, M., Pihlak, P., Aleksejenko, I., and Paršeliunas, E., 2016. The NKG2008 GPS campaign – final transformation results and a new common Nordic reference frame. *Journal of Geodetic Science*. Volume **6**, Issue **1**, ISSN (Online) 2081–9943, March 2016. DOI: https://doi.org/10.1515/jogs-2016-0001

IERS, 2019. International Earth Rotation and Reference Systems Service. https://www.iers.org/, accessed 12.3.2019.

IGS, 2019. International GNSS Service. http://www.igs.org/, accessed 12.3.2019.

IGS, 2018. IGS antenna files. ftp://ftp.igs.org/pub/station/general/

JHS184, 2017. JHS 184 Kiintopistemittaus EUREF-FIN-koordinaattijärjestelmässä. *Julkisen hallinnon suosituksia* no **184**. http://www.jhs-suositukset.fi/web/guest/jhs/recommendations/184

Jokela, J., 2014. Length in Geodesy – On Metrological Traceability of a Geospatial Measurand. *Publ. Finn. Geod. Inst.* **154**, 240 p. http://urn.fi/URN:ISBN:978-951-711-310-6.

Jokela, J., Būga, A., Putrimas, R., and Tulevičius, V., 2002. Analysis of repeatede calibration of Kyviškės baseline. *Geodezija ir Kartografija*, **28**:4, 125-130.

Kakkuri, J., Koivula, H., Ollikainen, M., Paunonen, M., Poutanen, M., and Vermeer, M., 1995. The Finnish Permanent GPS Array FinnNet: Current Status. Invited paper. IGS Workshop, Potsdam, May 12-17, 1995.

Kallio, U., Koivula, H., Lahtinen, S., Nikkonen, V., Poutanen, M., 2019. Validating and comparing GNSS antenna calibrations. *J Geod* (2019) **93**: 1. https://doi.org/10.1007/s00190-018-1134-2

Koivula, H., Ollikainen, M., and Poutanen, M., 1999a. The Finnish Permanent GPS Network - FinnRef. The XIII General Meeting of the Nordic Geodetic Commission, May 25.-29., 1998, Gävle, Sweden. *LMV rapport* 1999:12.

Koivula, H., 1999b. The First Results of the Finnish Permanent GPS Network. The XIII General Meeting of the Nordic Geodetic Commission, May 25.-29., 1998, Gävle, Sweden. *LMV rapport* 1999:12.

Koivula, H., Ollikainen, M., and Poutanen, M., 2002. Periodic effects in GPS time series. 27th General Assembly of the European Geophysical Society, Nice, France, 21-26 April, 2002. *Geophysical Research Abstracts* Volume **4**, 2002, Abstract number: EGS02-A-04383, ISSN: 1029-7006.

Kouba, J., Lahaye, F., and Tétreault, P., 2017. Precise Point Positioning, in: Teunissen P.J. and Montenbruck O. (eds), Springer Handbook of Global Navigation Satellite Systems, *Springer Handbooks*, Springer, Cham, 2017, 723-752.

Lahtinen, S., Häkli, P., Jivall, L., Kempe, C., Kollo, K., Kosenko, K., Pihlak, P., Prizginiene, D., Tangen, O., Weber, M., Parseliunas, E., Baniulis, R., and Galinauskas, K., 2018. First Results of the Nordic and Baltic GNSS Analysis Centre. *Journal of Geodetic Science*, **8**(1): 34-42. https://doi.org/10.1515/jogs-2018-0005

Landau H., Vollath U., and Chen, X., 2002. Virtual Reference Station Systems, *Journal of Global Positioning Systems* **1**(2): 137-143.

Lidberg, M., Johansson. J. M., Scherneck, H-G., and Milne, G. A., 2010. Recent results based on continuous GPS observations of the GIA process in Fennoscandia from BIFROST. *J Geodyn* **50**: 8–18, https://doi.org/10.1016/j.jog.2009.11.010

Mader, G. L., 1999. GPS antenna calibration at the national geodetic survey. *GPS solutions* **3**(1):50–58.

MMM, 2018. Report on spatial data policy. http://urn.fi/URN:ISBN:978-952-453-980-7.

NGA, 2014. Department of Defence World Geodetic System 1984: Its definition and relationship with local coordinate systems. *National Geospatial-Intelligence Agency (NGA) Standardization Document* NGA.STND.0036_1.0.0_WGS84 version 1.0.0 2014-07-08.

Odijk, D., 2017. Positioning Model, in: Teunissen P.J. and Montenbruck O. (eds), Springer Handbook of Global Navigation Satellite Systems, *Springer Handbooks*, Springer, Cham, 2017, 605-638.

Odijk, D., and Wanninger, L., 2017. Differential Positioning, in: Teunissen P.J. and Montenbruck O. (eds), Springer Handbook of Global Navigation Satellite Systems, *Springer Handbooks*, Springer, Cham, 2017, 753-780.

Ollikainen, M., Koivula, H., and Poutanen, M., 2000a. The densification of the EUREF network in Finland. *Publ. Finn.Geod. Inst.* **129**.

Ollikainen, M., Koivula, H., and Poutanen, M., 2000b. The Densification of the EUREF Network in Finland. IAG, Section I - Positioning, Commission X - Global and Regional Geodetic Networks, Sub-Commission for Europe (EUREF). Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Prague, 2-5 June 1999. Veröffentlichungen der Bayerischen Kommission für die Internationale Erdmessung der Bayerische Akademie der Wissenschaften, Astronomisch-Geodätische Arbeiten, Heft Nr. **60**. Münhen. pp. 114-122.

Paunonen, M., 1992. Height-stabolised 20-metre antenna mointing system of the CIGNET GPS station at Metsähovi. Paper presented in 7th International Symposium on Geodesy and Physics of the Earth, 5.-10.10.1992, Potsdam.

Penna, N. T., King, M. A., and Stewart, M. P., 2007. GPS height time series: Short-period origins of spurious long-period signals, *J. Geophys. Res.*, **112**, B02402, doi:10.1029/2005JB004047.

Petit, G., and Luzum, B., 2010. IERS Conventions (2010). *IERS Techical Note* No. **36**. Bundesamt für Kartographie und Geodäsie.

Pollinger F. et al., 2015. Metrology for Long Distance Surveying: A Joint Attempt to Improve Traceability of Long Distance Measurements. In: Rizos C., Willis P. (eds) IAG 150 Years. *International Association of Geodesy Symposia*, vol **143**. Springer.

Poutanen M., Jokela, J., Ollikainen, M., Koivula, H., Bilker, M., and Virtanen, H., 2005. Scale variation of GPS time series. A window on the future of geodesy. Ed. F. Sanso. *International Association of Geodesy Symposia* vol. **128**, p. 15-20.

Poutanen M., Ollikainen, M., Koivula, H., Bilker, M., Jokela, J., and Virtanen, H., 2004. Global periodic effects in GPS time series. In The state of GPS vertical positioning precsion: Separation of Earth processes by space geodesy. Luxembourg 2003. (Ed. T. van Dam and O. Francis) *Cahiers du Centre Européen de Géodynamique et de Séismologie*. Vol. **23**. p. 137-142.

Press, W. H., Teukolsky, S., Vetterling, W. T., and Flannery, B. P., 1996. Numerical Recipes in Fortran 77: the Art of Scientific Computing. Second Edition", vol. **1**, 1996. Cambridge University Press.

Rothacher, M., Schaer, S., Mervart, L., and Beutler, G., 1995. Determination of antenna phase center variation using GPS data. In: IGS Workshop Special Topics and New Directions, May 15-18, Potsdam, Germany.

Rothacher, M., and Mervart, L., 1996. The Bernese GPS software version 4.0. Astron. Inst., Univ. of Berne, Berne, Switzerland, 1996.

Wübbena, G., and Bagge, A., 2002. RTCM Message Type 59-FKP for Transmission of FKP. *Geo++® White Paper*, **17**. April 2002, Garbsen.

Suomen Geodeettisen laitoksen julkaisut:
Veröffentlichungen des Finnischen Geodätischen Institutes:
Publications of the Finnish Geodetic Institute:

1. Y. VÄISÄLÄ: Tafeln für geodätische Berechnungen nach den Erddimensionen von Hayford. Helsinki 1923. 30 S.
2. Y. VÄISÄLÄ: Die Anwendung der Lichtinterferenz zu Längenmessungen auf grösseren Distanzen. Helsinki 1923. 22 S.
3. ILMARI BONSDORFF, Y. LEINBERG, W. HEISKANEN: Die Beobachtungsergebnisse der südfinnischen Triangulation in den Jahren 1920-1923. Helsinki 1924. 235 S.
4. W. HEISKANEN: Untersuchungen über Schwerkraft und Isostasie. Helsinki 1924. 96 S. 1 Karte.
5. W. HEISKANEN: Schwerkraft und isostatische Kompensation in Norwegen. Helsinki 1926. 33 S. 1 Karte.
6. W. HEISKANEN: Die Erddimensionen nach den europäischen Gradmessungen. Helsinki 1926. 26 S.
7. ILMARI BONSDORFF, V.R. ÖLANDER, Y. LEINBERG: Die Beobachtungsergebnisse der südfinnischen Triangulation in den Jahren 1924-1926. Helsinki 1927. 164 S. 1 Karte.
8. V.R. ÖLANDER: Ausgleichung einer Dreieckskette mit Laplaceschen Punkten. Helsinki 1927. 49 S. 1 Karte.
9. U. PESONEN: Relative Bestimmungen der Schwerkraft auf den Dreieckspunkten der südfinnischen Triangulation in den Jahren 1924-1925. Helsinki 1927. 129 S.
10. ILMARI BONSDORFF: Das Theorem von Clairaut und die Massenverteilung im Erdinnern. Helsinki 1929. 10 S.
11. ILMARI BONSDORFF, V.R. ÖLANDER, W. HEISKANEN, U. PESONEN: Die Beobachtungsergebnisse der Triangulationen in den Jahren 1926-1928. Helsinki 1929. 139 S. 1 Karte.
12. W. HEISKANEN: Über die Elliptizität des Erdäquators. Helsinki 1929. 18 S.
13. U. PESONEN: Relative Bestimmungen der Schwerkraft in Finnland in den Jahren 1926-1929. Helsinki 1930. 168 S. 1 Karte.
14. Y. VÄISÄLÄ: Anwendung der Lichtinterferenz bei Basismessungen. Helsinki 1930. 47 S.
15. M. FRANSSILA: Der Einfluss der den Pendel umgebenden Luft auf die Schwingungszeit beim v. Sterneckschen Pendelapparat. Helsinki 1931. 23 S.
16. Y. LEINBERG: Ergebnisse der astronomischen Ortsbestimmungen auf den finnischen Dreieckspunkten. Helsinki 1931. 162 S.
17. V.R. ÖLANDER: Über die Beziehung zwischen Lotabweichungen und Schwereanomalien sowie über das Lotabweichungssystem in Süd-Finnland. Helsinki 1931. 23 S.
18. PENTTI KALAJA, UUNO PESONEN, V.R. ÖLANDER, Y. LEINBERG: Beobachtungsergebnisse. Helsinki 1933. 240 S. 1 Karte.
19. R.A. HIRVONEN: The continental undulations of the geoid. Helsinki 1934. 89 pages. 1 map.
20. ILMARI BONSDORFF: Die Länge der Versuchsbasis von Helsinki und Längenveränderungen der Invardrähte 634-637. Helsinki 1934. 41 S.
21. V.R. ÖLANDER: Zwei Ausgleichungen des grossen südfinnischen Dreieckskranzes. Helsinki 1935. 66 S. 1 Karte.
22. U. PESONEN, V.R. ÖLANDER: Beobachtungsergebnisse. Winkelmessungen in den Jahren 1932-1935. Helsinki 1936. 148 S. 1 Karte.
23. R.A. HIRVONEN: Relative Bestimmungen der Schwerkraft in Finnland in den Jahren 1931, 1933 und 1935. Helsinki 1937. 151 S.
24. R.A. HIRVONEN: Bestimmung des Schwereunterschiedes Helsinki-Potsdam im Jahre 1935 und Katalog der finnischen Schwerestationen. Helsinki 1937. 36 S. 1 Karte.
25. T.J. KUKKAMÄKI: Über die nivellitische Refraktion. Helsinki 1938. 48 S.
26. Finnisches Geodätisches Institut 1918-1938. Helsinki 1939. 126 S. 2 Karten.
27. T.J. KUKKAMÄKI: Formeln und Tabellen zur Berechnung der nivellitischen Refraktion. Helsinki 1939. 18 S.
28. T.J. KUKKAMÄKI: Verbesserung der horizontalen Winkelmessungen wegen der Seitenrefraktion. Helsinki 1939. 18 S.
29. ILMARI BONSDORFF: Ergebnisse der astronomischen Ortsbestimmungen im Jahre 1933. Helsinki 1939. 47 S.
30. T. HONKASALO: Relative Bestimmungen der Schwerkraft in Finnland im Jahre 1937. Helsinki 1941. 78 S.
31. PENTTI KALAJA: Die Grundlinienmessungen des Geodätischen Institutes in den Jahren 1933-1939 nebst Untersuchungen über die Verwendung der Invardrähte. Helsinki 1942. 149 S.
32. U. PESONEN, V.R. ÖLANDER: Beobachtungsergebnisse. Winkelmessungen in den Jahren 1936-1940. Helsinki 1942. 165 S. 1 Karte.
33. PENTTI KALAJA: Astronomische Ortsbestimmungen in den Jahren 1935-1938. Helsinki 1944. 142 S.
34. V.R. ÖLANDER: Astronomische Azimutbestimmungen auf den Dreieckspunkten in den Jahren 1932-1938; Lotabweichungen und Geoidhöhen. Helsinki 1944. 107 S. 1 Karte.
35. U. PESONEN: Beobachtungsergebnisse. Winkelmessungen in den Jahren 1940-1947. Helsinki 1948. 165 S. 1 Karte.
36. Professori Ilmari Bonsdorffille hänen 70-vuotispäivänään omistettu juhlajulkaisu. Publication dedicated to Ilmari Bonsdorff on the occasion of his 70th anniversary. Helsinki 1949. 262 pages. 13 maps.
37. TAUNO HONKASALO: Measuring of the 864 m-long Nummela standard base line with the Väisälä light interference comparator and some investigations into invar wires. Helsinki 1950. 88 pages.
38. V.R. ÖLANDER: On the geoid in the Baltic area and the orientation of the Baltic Ring. Helsinki 1950. 26 pages.
39. W. HEISKANEN: On the world geodetic system. Helsinki 1951. 25 pages.
40. R.A. HIRVONEN: The motions of Moon and Sun at the solar eclipse of 1947 May 20th. Helsinki 1951. 36 pages.
41. PENTTI KALAJA: Catalogue of star pairs for northern latitudes from 55° to 70°for astronomic determination of latitudes by the Horrebow-Talcott method. Helsinki 1952. 191 pages.
42. ERKKI KÄÄRIÄINEN: On the recent uplift of the Earth's crust in Finland. Helsinki 1953. 106 pages. 1 map.
43. PENTTI KALAJA: Astronomische Ortsbestimmungen in den Jahren 1946-1948. Helsinki 1953. 146 S.
44. T.J. KUKKAMÄKI, R.A. HIRVONEN: The Finnish solar eclipse expeditions to the Gold Coast and Brazil 1947. Helsinki 1954. 71 pages.
45. JORMA KORHONEN: Einige Untersuchungen über die Einwirkung der Abrundungsfehler bei Gross-Ausgleichungen. Neu-Ausgleichung des südfinnischen Dreieckskranzes. Helsinki 1954. 138 S. 3 Karten.

46. Professori Weikko A. Heiskaselle hänen 60-vuotispäivänään omistettu juhlajulkaisu. Publication dedicated to Weikko A. Heiskanen on the occasion of his 60th anniversary. Helsinki 1955. 214 pages.
47. Y. Väisälä: Bemerkungen zur Methode der Basismessung mit Hilfe der Lichtinterferenz. Helsinki 1955. 12 S.
48. U. Pesonen, Tauno Honkasalo: Beobachtungsergebnisse der finnischen Triangulationen in den Jahren 1947-1952. Helsinki 1957. 91 S.
49. Pentti Kalaja: Die Zeiten von Sonnenschein, Dämmerung und Dunkelheit in verschiedenen Breiten. Helsinki 1958. 63 S.
50. V.R. Ölander: Astronomische Azimutbestimmungen auf den Dreieckspunkten in den Jahren 1938-1952. Helsinki 1958. 90 S. 1 Karte.
51. Jorma Korhonen, V.R. Ölander, Erkki Hytönen: The results of the base extension nets of the Finnish primary triangulation. Helsinki 1959. 57 pages. 5 appendices. 1 map.
52. V.R. Ölander: Vergleichende Azimutbeobachtungen mit vier Instrumenten. Helsinki 1960. 48 pages.
53. Y. Väisälä, L. Oterma: Anwendung der astronomischen Triangulationsmethode. Helsinki 1960. 18 S.
54. V.R. Ölander: Astronomical azimuth determinations on trigonometrical stations in the years 1955-1959. Helsinki 1961. 15 pages.
55. Tauno Honkasalo: Gravity survey of Finland in years 1945-1960. Helsinki 1962. 35 pages. 3 maps.
56. Erkki Hytönen: Beobachtungsergebnisse der finnischen Triangulationen in den Jahren 1953-1962. Helsinki 1963. 59 S.
57. Erkki Kääriäinen: Suomen toisen tarkkavaaituksen kiintopisteluettelo I. Bench mark list I of the Second Levelling of Finland. Helsinki 1963. 164 pages. 2 maps.
58. Erkki Hytönen: Beobachtungsergebnisse der finnischen Triangulationen in den Jahren 1961-1962. Helsinki 1963. 32 S.
59. Aimo Kiviniemi: The first order gravity net of Finland. Helsinki 1964. 45 pages.
60. V.R. Ölander: General list of astronomical azimuths observed in 1920-1959 in the primary triangulation net. Helsinki 1965. 47 pages. 1 map.
61. Erkki Kääriäinen: The second levelling of Finland in 1935-1955. Helsinki 1966. 313 pages. 1 map.
62. Jorma Korhonen: Horizontal angles in the first order triangulation of Finland in 1920-1962. Helsinki 1966. 112 pages. 1 map.
63. Erkki Hytönen: Measuring of the refraction in the Second Levelling of Finland. Helsinki 1967. 18 pages.
64. Jorma Korhonen: Coordinates of the stations in the first order triangulation of Finland. Helsinki 1967. 42 pages. 1 map.
65. Geodeettinen laitos - The Finnish Geodetic Institute 1918-1968. Helsinki 1969. 147 pages. 4 maps.
66. Juhani Kakkuri: Errors in the reduction of photographic plates for the stellar triangulation. Helsinki 1969. 14 pages.
67. Pentti Kalaja, V.R. Ölander: Astronomical determinations of latitude and longitude in 1949-1958. Helsinki 1970. 242 pages. 1 map.
68. Erkki Kääriäinen: Astronomical determinations of latitude and longitude in 1954-1960. Helsinki 1970. 95 pages. 1 map.
69. Aimo Kiviniemi: Niinisalo calibration base line. Helsinki 1970. 36 pages. 1 sketch appendix.
70. Teuvo Parm: Zero-corrections for tellurometers of the Finnish Geodetic Institute. Helsinki 1970. 18 pages.
71. Erkki Kääriäinen: Astronomical determinations of latitude and longitude in 1961-1966. Helsinki 1971. 102 pages. 1 map.
72. Juhani Kakkuri: Plate reduction for the stellar triangulation. Helsinki 1971. 38 pages.
73. V.R. Ölander: Reduction of astronomical latitudes and longitudes 1922-1948 into FK4 and CIO systems. Helsinki 1972. 40 pages.
74. Juhani Kakkuri and Kalevi Kalliomäki: Photoelectric time micrometer. Helsinki 1972. 53 pages.
75. Erkki Hytönen: Absolute gravity measurement with long wire pendulum. Helsinki 1972. 142 pages.
76. Juhani Kakkuri: Stellar triangulation with balloon-borne beacons. Helsinki 1973. 48 pages.
77. Jussi Kääriäinen: Beobachtungsergebnisse der finnischen Winkelmessungen in den Jahren 1969-70. Helsinki 1974. 40 S.
78. Aimo Kiviniemi: High precision measurements for studying the secular variation in gravity in Finland. Helsinki 1974. 64 pages.
79. Teuvo Parm: High precision traverse of Finland. Helsinki 1976. 64 pages.
80. R.A. Hirvonen: Precise computation of the precession. Helsinki 1976. 25 pages.
81. Matti Ollikainen: Astronomical determinations of latitude and longitude in 1972-1975. Helsinki 1977. 90 pages. 1 map.
82. Juhani Kakkuri and Jussi Kääriäinen: The Second Levelling of Finland for the Aland archipelago. Helsinki 1977. 55 pages.
83. Mikko Takalo: Suomen Toisen tarkkavaaituksen kiintopisteluettelo II. Bench mark list II of the Second Levelling of Finland. Helsinki 1977. 150 sivua.
84. Matti Ollikainen: Astronomical azimuth determinations on triangulation stations in 1962-1970. Helsinki 1977. 47 pages. 1 map.
85. Markku Heikkinen: On the tide-generating forces. Helsinki 1978. 150 pages.
86. Pekka Lehmuskoski and Jaakko Mäkinen: Gravity measurements on the ice of Bothnian Bay. Helsinki 1978. 27 pages.
87. T.J. Kukkamäki: Väisälä interference comparator. Helsinki 1978. 49 pages.
88. Jussi Kääriäinen: Observing the Earth Tides with a long water-tube tiltmeter. Helsinki 1979. 74 pages.
89. Publication dedicated to T.J. Kukkamäki on the occasion of his 70th anniversary. Helsinki 1979. 184 pages.
90. B. Ducarme and J. Kääriäinen: The Finnish Tidal Gravity Registrations in Fennoscandia. Helsinki 1980. 43 pages.
91. Aimo Kiviniemi: Gravity measurements in 1961-1978 and the results of the gravity survey of Finland in 1945-1978. Helsinki 1980. 18 pages. 3 maps.
92. Liisi Oterma: Programme de latitude du tube zénithal visuel de l'observatoire Turku-Tuorla systéme amélioré de 1976. Helsinki 1981. 18 pages.
93. Juhani Kakkuri, Aimo Kiviniemi and Raimo Konttinen: Contributions from the Finnish Geodetic Institute to the Tectonic Plate Motion Studies in the Area between the Pamirs and Tien-Shan Mountains. Helsinki 1981. 34 pages.
94. Jussi Kääriäinen: Measurement of the Ekeberg baseline with invar wires. Helsinki 1981. 17 pages.
95. Matti Ollikainen: Astronomical determinations of latitude and longitude in 1976-1980. Helsinki 1982. 90 pages. 1 map.
96. Raimo Konttinen: Observation results. Angle measurements in 1977-1978. Helsinki 1982. 29 pages.

97. G.P. Arnautov, Ye N. Kalish, A. Kiviniemi, Yu F. Stus, V.G. Tarasiuk, S.N. Scheglov: Determination of absolute gravity values in Finland using laser ballistic gravimeter. Helsinki 1982. 18 pages.
98. Leena Mikkola (editor): Mean height map of Finland. Helsinki 1983. 3 pages. 1 map.
99. Mikko Takalo and Jaakko Mäkinen: The Second Levelling of Finland for Lapland. Helsinki 1983. 144 pages.
100. Jussi Kääriäinen: Baseline Measurements with invar wires in Finland 1958-1970. Helsinki 1984. 78 pages.
101. Raimo Konttinen: Plate motion studies in Central Asia. Helsinki 1985. 31 pages.
102. Raimo Konttinen: Observation results. Angle measurements in 1979-1983. Helsinki 1985. 30 pages.
103. J. Kakkuri, T.J. Kukkamäki, J.-J. Levallois et H. Moritz: Le 250^{e} anniversaire de la mesure de l'arc du meridien en Laponie. Helsinki 1986. 60 pages.
104. G. Asch, T. Jahr, G. Jentzsch, A. Kiviniemi and J. Kääriäinen: Measurements of Gravity Tides along the "Blue Road Geotraverse" in Fennoscandia. Helsinki 1987. 57 pages.
105. Jussi Kääriäinen, Raimo Konttinen, Lu Qiankun and Du Zong Yu: The Chang Yang Standard Baseline. Helsinki 1986. 36 pages.
106. E.W. Grafarend, H. Kremers, J. Kakkuri and M. Vermeer: Adjusting the SW Finland Triangular Network with the TAGNET 3-D operational geodesy software. Helsinki 1987. 60 pages.
107. Matti Ollikainen: Astronomical determinations of latitude and longitude in 1981-1983. Helsinki 1988. 37 pages.
108. Markku Poutanen: Observation results. Angle measurements in 1967-1973. Helsinki 1988. 35 pages.
109. Jussi Kääriäinen, Raimo Konttinen and Zsuzsanna Németh: The Gödöllö Standard Baseline. Helsinki 1988. 66 pages.
110. Jussi Kääriäinen and Hannu Ruotsalainen: Tilt measurements in the underground laboratory Lohja 2, Finland, in 1977-1987. Helsinki 1989. 37 pages.
111. Mikko Takalo: Lisäyksiä ja korjauksia Suomen tarkkavaaitusten linjastoon 1977-1989. Helsinki 1991. 98 sivua.
112. Raimo Konttinen: Observation results. Angle measurements in the Pudasjärvi loop in 1973-1976. Helsinki 1991. 42 pages.
113. Raimo Konttinen, Jorma Jokela and Li Quan: The remeasurement of the Chang Yang Standard Baseline. Helsinki 1991. 40 pages.
114. Jussi Kääriäinen, Raimo Konttinen and Markku Poutanen: Interference measurements of the Nummela Standard Baseline in 1977, 1983, 1984 and 1991. Helsinki 1992. 78 pages.
115. Juhani Kakkuri (editor): Geodesy and geophysics. Helsinki 1993. 200 pages.
116. Jaakko Mäkinen, Heikki Virtanen, Qiu Qi-xian and Gu Liang-rong: The Sino-Finnish absolute gravity campaign in 1990. Helsinki 1993. 49 pages.
117. Raimo Konttinen: Observation results. Geodimeter observations in 1971-72, 1974-80 and 1984-85. Helsinki 1994. 58 pages.
118. Raimo Konttinen: Observation results. Angle measurements in 1964-65, 1971, 1984 and 1986-87. Helsinki 1994. 67 pages.
119. Jorma Jokela: The 1993 adjustment of the Finnish First-Order Terrestrial Triangulation. Helsinki 1994. 137 pages.
120. Markku Poutanen (editor): Interference measurements of the Taoyuan Standard Baseline. Helsinki 1995. 35 pages.
121. Jorma Jokela: Interference measurements of the Chang Yang Standard Baseline in 1994. Kirkkonummi 1996. 32 pages.
122. Olli Jaakkola: Quality and automatic generalization of land cover data. Kirkkonummi 1996. 39 pages.
123. Matti Ollikainen: Determination of orthometric heights using GPS levelling. Kirkkonummi 1997. 143 pages.
124. Tiina Kilpeläinen: Multiple Representation and Generalization of Geo-Databases for Topographic Maps. Kirkkonummi 1997. 229 pages.
125. Jussi Kääriäinen and Jaakko Mäkinen: The 1979-1996 gravity survey and the results of the gravity survey of Finland 1945-1996. Kirkkonummi 1997. 24 pages. 1 map.
126. Zhitong Wang: Geoid and crustal structure in Fennoscandia. Kirkkonummi 1998. 118 pages.
127. Jorma Jokela and Markku Poutanen: The Väisälä baselines in Finland. Kirkkonummi 1998. 61 pages.
128. Markku Poutanen: Sea surface topography and vertical datums using space geodetic techniques. Kirkkonummi 2000. 158 pages
129. Matti Ollikainen, Hannu Koivula and Markku Poutanen: The Densification of the EUREF Network in Finland. Kirkkonummi 2000. 61 pages.
130. Jorma Jokela, Markku Poutanen, Zhao Jingzhan, Pei Weili, Hu Zhenyuan and Zhang Shengshu: The Chengdu Standard Baseline. Kirkkonummi 2000. 46 pages.
131. Jorma Jokela, Markku Poutanen, Zsuzsanna Németh and Gábor Virág: Remeasurement of the Gödöllö Standard Baseline. Kirkkonummi 2001. 37 pages.
132. Andres Rüdja: Geodetic Datums, Reference Systems and Geodetic Networks in Estonia. Kirkkonummi 2004. 311 pages.
133. Heikki Virtanen: Studies of Earth Dynamics with the Superconducting Gravimeter. Kirkkonummi 2006. 130 pages.
134. Juha Oksanen: Digital elevation model error in terrain analysis. Kirkkonummi 2006. 142 pages. 2 maps.
135. Matti Ollikainen: The EUVN-DA GPS campaign in Finland. Kirkkonummi 2006. 42 pages.
136. Annu-Maaria Nivala: Usability perspectives for the design of interactive maps. Kirkkonummi 2007. 157 pages.
137. Xiaowei Yu: Methods and techniques for forest change detection and growth estimation using airborne laser scanning data. Kirkkonummi 2007. 132 pages.
138. Lassi Lehto: Real-time content transformations in a WEB service-based delivery architecture for geographic information. Kirkkonummi 2007. 150 pages.
139. Pekka Lehmuskoski, Veikko Saaranen, Mikko Takalo and Paavo Rouhiainen: Suomen Kolmannen tarkkavaaituksen kiintopisteluettelo. Bench Mark List of the Third Levelling of Finland. Kirkkonummi 2008. 220 pages.
140. Eija Honkavaara: Calibrating digital photogrammetric airborne imaging systems using a test field. Kirkkonummi 2008. 139 pages.
141. Markku Poutanen, Eero Ahokas, Yuwei Chen, Juha Oksanen, Marita Portin, Sari Ruuhela, Heli Suurmäki (editors): Geodeettinen laitos – Geodetiska Institutet – Finnish Geodetic Institute 1918–2008. Kirkkonummi 2008. 173 pages.

142. Mika Karjalainen: Multidimensional SAR Satellite Images – a Mapping Perspective. Kirkkonummi 2010. 132 pages.
143. Maaria Nordman: Improving GPS time series for geodynamic studies. Kirkkonummi 2010. 116 pages.
144. Jorma Jokela and Pasi Häkli: Interference measurements of the Nummela Standard Baseline in 2005 and 2007. Kirkkonummi 2010. 85 pages.
145. Eetu Puttonen: Tree Species Classification with Multiple Source Remote Sensing Data. Kirkkonummi 2012. 162 pages.
146. Juha Suomalainen: Empirical Studies on Multiangular, Hyperspectral, and Polarimetric Reflectance of Natural Surfaces. Kirkkonummi 2012. 144 pages.
147. Leena Matikainen: Object-based interpretation methods for mapping built-up areas. Kirkkonummi 2012. 210 pages.
148. Lauri Markelin: Radiometric calibration, validation and correction of multispectral photogrammetric imagery. Kirkkonummi 2013. 160 pages.
149. Xinlian Liang: Feasibility of Terrestrial Laser Scanning for Plotwise Forest Inventories. Kirkkonummi 2013. 150 pages.
150. Eero Ahokas: Aspects of accuracy, scanning angle optimization, and intensity calibration related to nationwide laser scanning. Kirkkonummi 2013. 124 pages.
151. Laura Ruotsalainen: Vision-Aided Pedestrian Navigation for Challenging GNSS Environments. Kirkkonummi 2013. 180 pages.
152. Harri Kaartinen: Benchmarking of airborne laser scanning based feature extraction methods and mobile laser scanning system performance based on high-quality test fields. Kirkkonummi 2013. 346 pages.
153. Antero Kukko: Mobile Laser Scanning – System development, performance and applications. Kirkkonummi 2013. 247 pages.
154. Jorma Jokela: Length in Geodesy – On Metrological Traceability of a Geospatial Measurand. Kirkkonummi 2014. 240 pages.
155. Pyry Kettunen: Analysing landmarks in nature and elements of geospatial images to support wayfinding. Kirkkonummi 2014. 281 pages.
156. MARI LAAKSO: Improving Accessibility for Pedestrians with Geographic Information. Kirkkonummi 2014. 129 pages.
157. LINGLI ZHU: A Pipeline of 3D Scene Reconstruction from Point Clouds. Kirkkonummi 2015. 206 pages.
158. ROBERT GUINNESS: Context Awareness for Navigation Applications. Kirkkonummi 2015. 244 pages.
159. HANNU KOIVULA: Finnish permanent GNSS network FinnRef – evolution towards a versatile positioning service. Helsinki 2019. 141 pages.

Finnish Geospatial Research Institute FGI
Geodeetinrinne 2
FI-02430 Masala
Finland

www.fgi.fi