RTK in Industry and Practical Work

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Motivation to Select a Topic …

- Geo++ is a company with **main focus** on
  - **development of GNSS software** and applications
  - system conception and design
  - research and analysis
  - project management
  - consulting

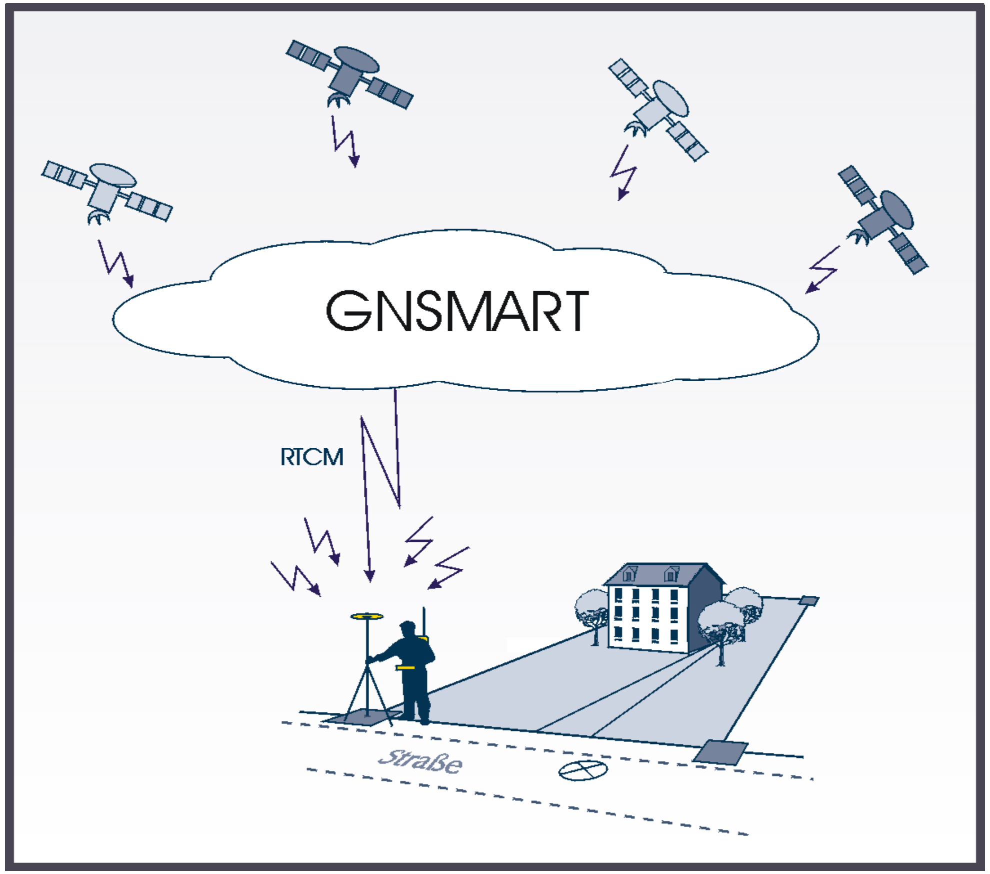
- in all fields of GNSS-based positioning and navigation

- **RTK in Industry** and Practical Work
  - variety of GNSS applications with requirements
  - accuracy, static vs kinematic, real-time vs post-processing, near-real-time processing, integrity, accessibility, …

RTK/PPP – Ideal System

- **reception of all necessary** reference and correction **data**
- flexible **communication** using different communication media (uni- or bi-directional)
- determination of **absolute position**
- (better) **1 cm accuracy**

  - everywhere
  - every time
  - static/kinematic



Geo++ figure from the late 1990s

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  - variety of GNSS applications with requirements
  - accuracy, static vs kinematic, real-time vs post-processing, near-real-time processing, integrity, accessibility, …

- RTK in Industry **and Practical Work**
  - there are important issues in practical work while setting-up RTK Networks

Practical Work - Setting-Up a RTK Network

(incomplete list of keywords)

- **GNSS antenna** correction
  - antenna type, consistent corrections, antenna orientations NRP, reference point ARP, PCV, GDV, GLONASS PCV, satellite PCV, …
- **station setup**/environment
  - station quality, multipath, near-field multipath, far-field multipath, …
- **coordinates**
  - verification, determination, official and technical coordinates, Datum, transformation to ITRF, plate-tectonics, station velocity, tectonic events, site displacement, local transformation, national system, height system, geoid, …

Practical Work - Setting-Up a RTK Network

(incomplete list of keywords)

- **GNSS** satellite and receiver **biases**
  - receiver type, firmware, signals, GLONASS Code-Phase Bias, biases like QIX* biases, 125* biases, GGG* biases, …
- dissemination of **GNSS correction** data
  - standardized format, parametrization of corrections (PRS, VRS, FKP, MAC, SSR), broadcast service vs bi-directional service, communication link, bandwidth requirements, scalable services, access control, encryption, …

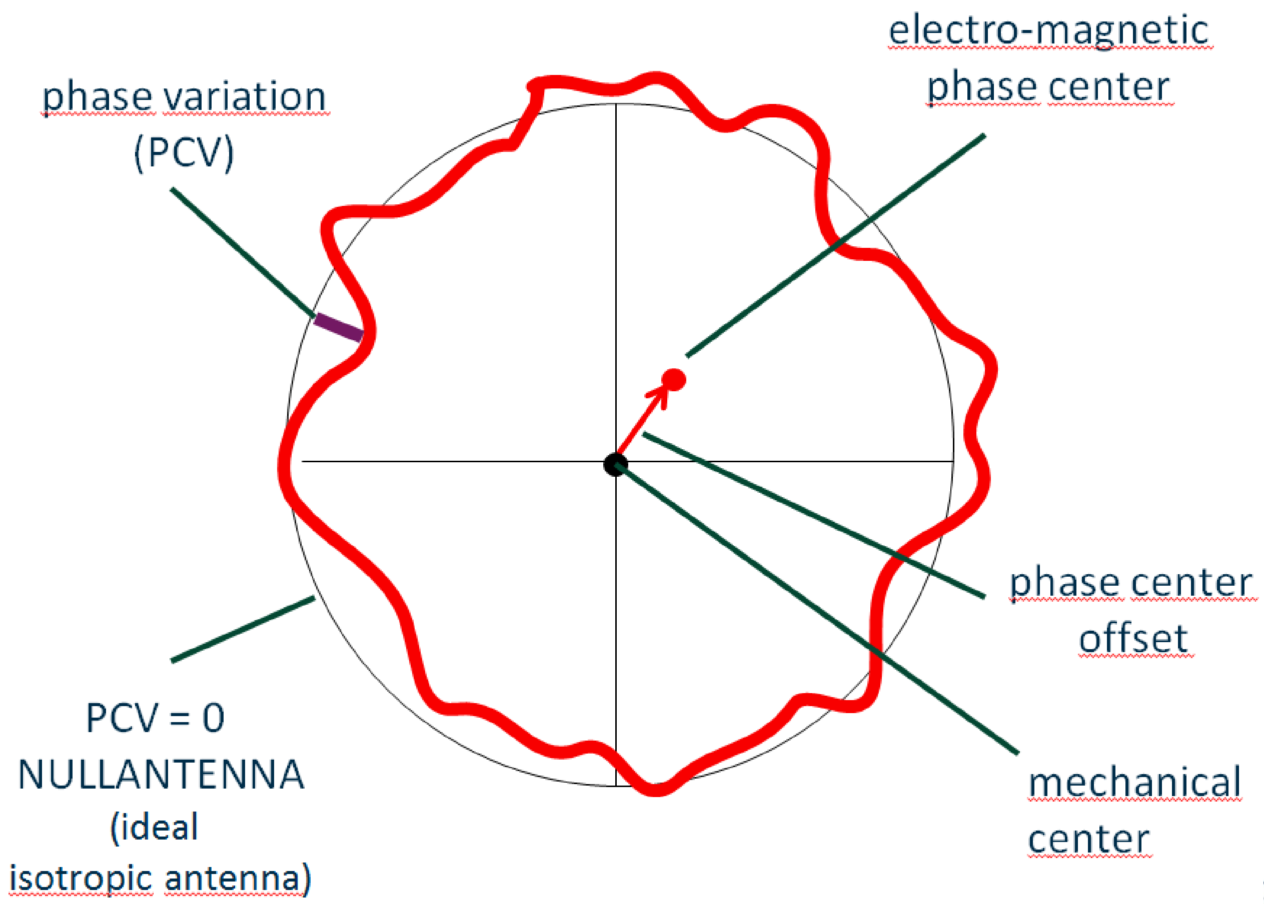
* Geo++ terminology for biases

Outline

- Practical Work - Setting-Up a RTK Network:
  GNSS Antenna/Near- and Far-Field Impact
  - GNSS Antenna Correction (1)
  - Some Details on absolute PCV Field Calibration
  - GNSS Antenna Correction (2)
  - Insight from Series of GNSS Antenna Calibrations
  - GNSS Antenna Group Delay Variation
  - Near- and Far-Field Impact
  - Excursion - GNSS Satellite Antenna
  - Excursion - Historical Review
  - Summary/Outlook

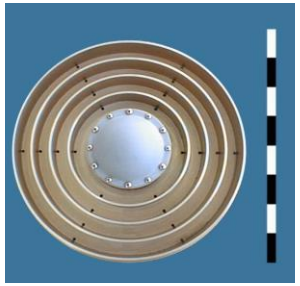
GNSS Antenna Correction

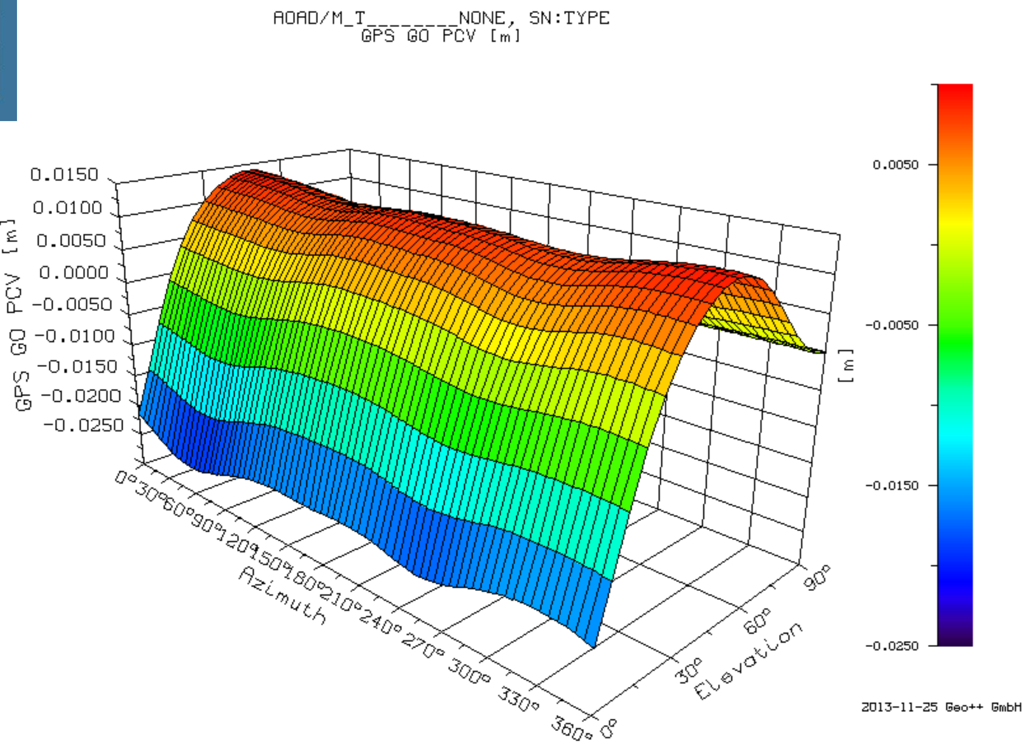
- status late **1990s**
  - **problems** with antenna corrections from existing relative field calibration methods
  - **problems** with antenna corrections from absolute chamber calibration
  - phase center and variation (**PCV**) corrections urgently **needed** for GPS (and later for GLONASS) applications with **mixed antenna types** (eg Network RTK, precise engineering tasks, …)



GNSS Antenna Correction

- **requirements** specified for an GNSS antenna calibration method
  - **separation of** phase center and variation (PCV) and **multipath effects** (MP)
  - **absolute PCV** (independent from any reference antenna)
  - **high** resolution and **accuracy** of determined PCV
  - **independent from station and location** (eg MP and geographic latitude)
  - **field calibration** method

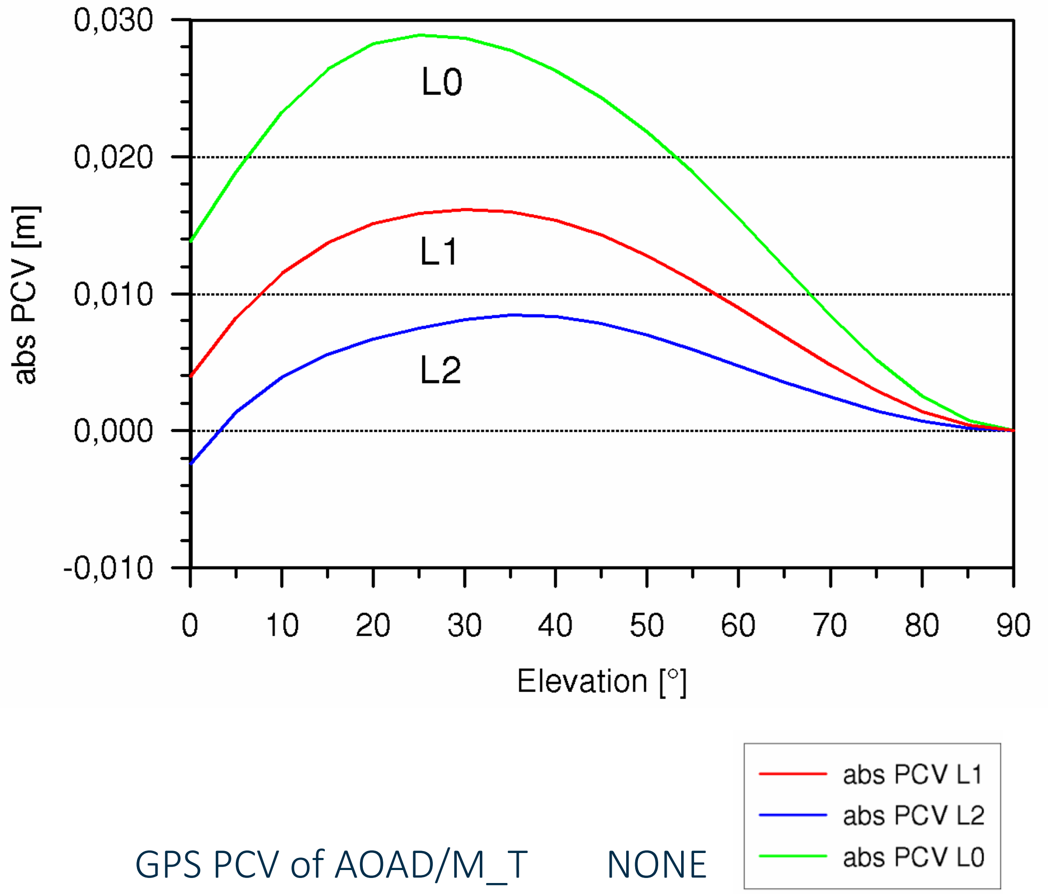




AOAD/M_T NONE GPS L0 PCV without offset)

Absolute* vs Relative PCV Corrections

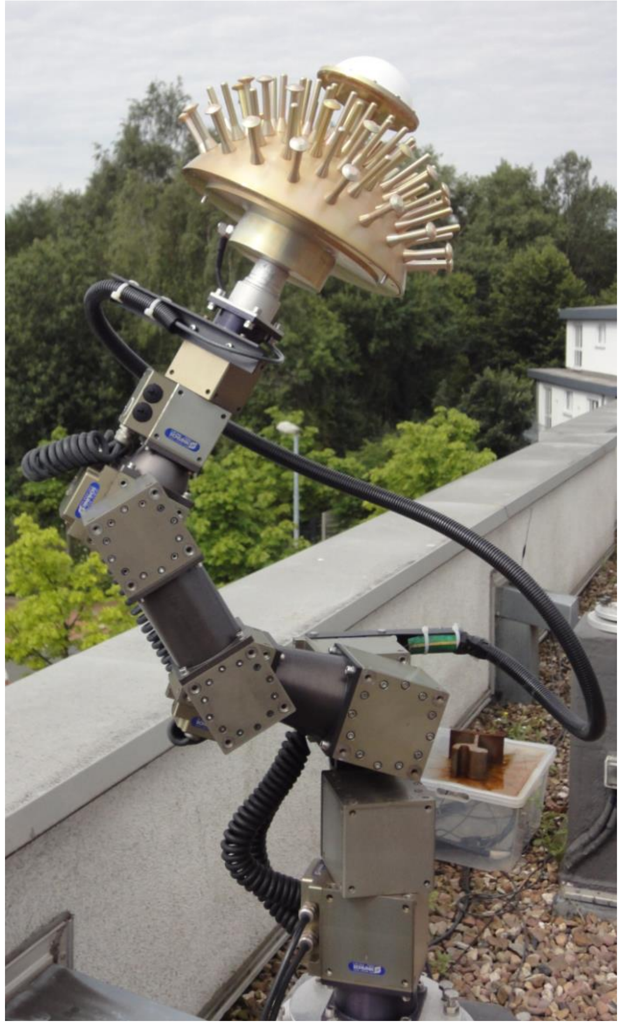
- **relative PCV** corrections
  - **reference antenna** defined
    AOAD/M_T NONE
  - normalization of PCV of any antenna
    to reference antenna by relative calibration
- systematic biases caused by relative PCV are
  - increasing with distance
  - affecting modelling (eg troposphere)
  - affecting ambiguity resolution
- **absolute PCV** corrections
  - independent from reference antenna



GPS PCV of AOAD/M_T NONE

GNSS Antenna Calibration

- characteristics of Geo++ GNPCV service today
- primary task of calibration
  - **absolute***
    phase center and -**variation** (PCV)
- robot excellent instrument to determine additional parameters
  - **signal strength** (carrier-to-noise, CN0 pattern)
  - **Group Delay Variations** (GDV) / Code calibration
  - **near-field impact** on antenna
- separation of multipath in near-field and far-field effects
  - absolute **station calibration** of multipath
- antenna calibration provides (since 2000, GLO 2006, GDV 2008)
  - GPS + GLO L1 and L2 PCV
  - GPS + GLO S1 and S2 CNV
  - GPS + GLO P1 and P2 GDV



Geo++ robot withTPSPN_A5 NONE

* without impact of a reference antenna

Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

Development of Automated Antenna Mount

- **orientation changes** of GNSS antenna **required**
- **mount for rotating and tilting** GNSS antenna
  - precise, fixed and stable rotation point
  - automation
  - operational procedure
- finally use of a **robot**
  - fast changes
  - automated robot guidance
  - real-time

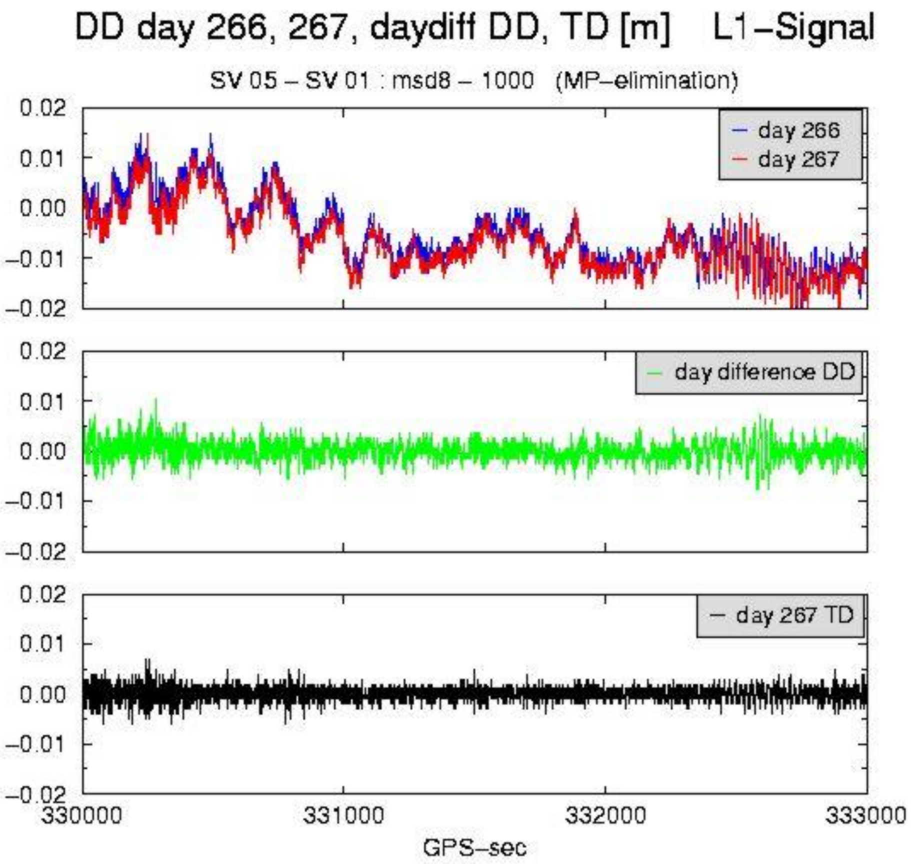
1996

1998

2000

close cooperation with
Institut für Erdmessung, **Universität, Hannover**

Multipath Elimination Techniques and PCV Separation

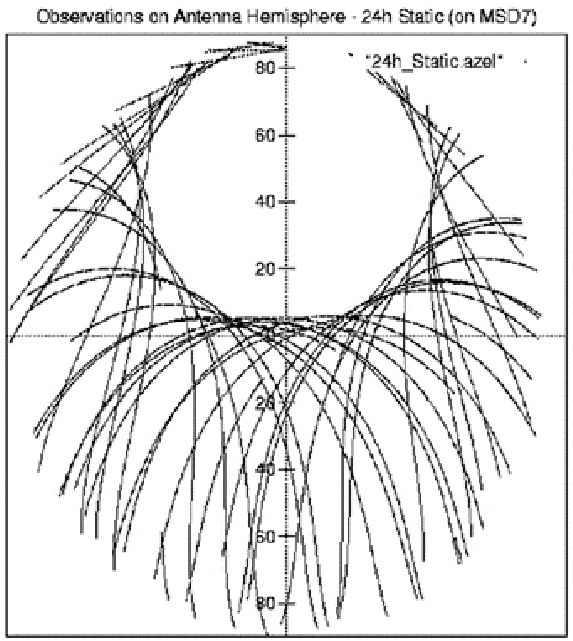


- **first approach** (1997)
  - **siderial differences** in post-processing
  - observation on two days
  - same geometry/environment eliminates MP
- **current approach** (since 2000)
  - **short-term differences** in **real-time**
  - same MP for subsequent epochs eliminates MP
- **PCV reintroduced by orientation changes** (rotations and tilts)

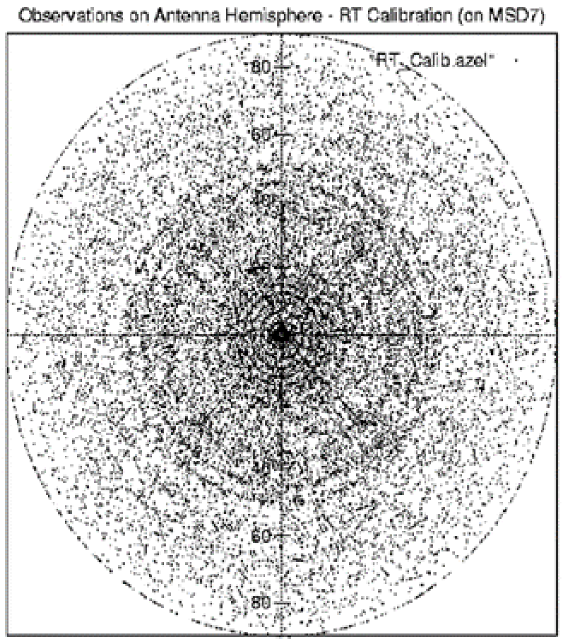
Details on absolute PCV Field Calibration

- **homogeneous coverage** of antenna
  - 6000 - 8000 different robot positions
- **dynamic robot guidance** in real-time
  - depending on satellite constellation
  - optimizes observation time
- **dynamic elevations mask**
  - uses high elevation satellites (>18°)
  - increase of cut-off in tilted positions
  - uses negative elevation (-5°)
- stochastic **modeling of remaining multipath** for every satellite

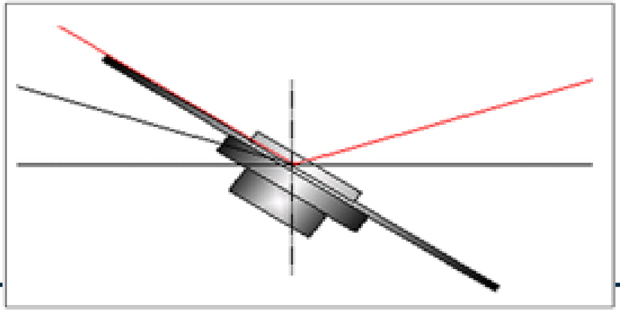
GNSS observation coverage



relative antenna calibration

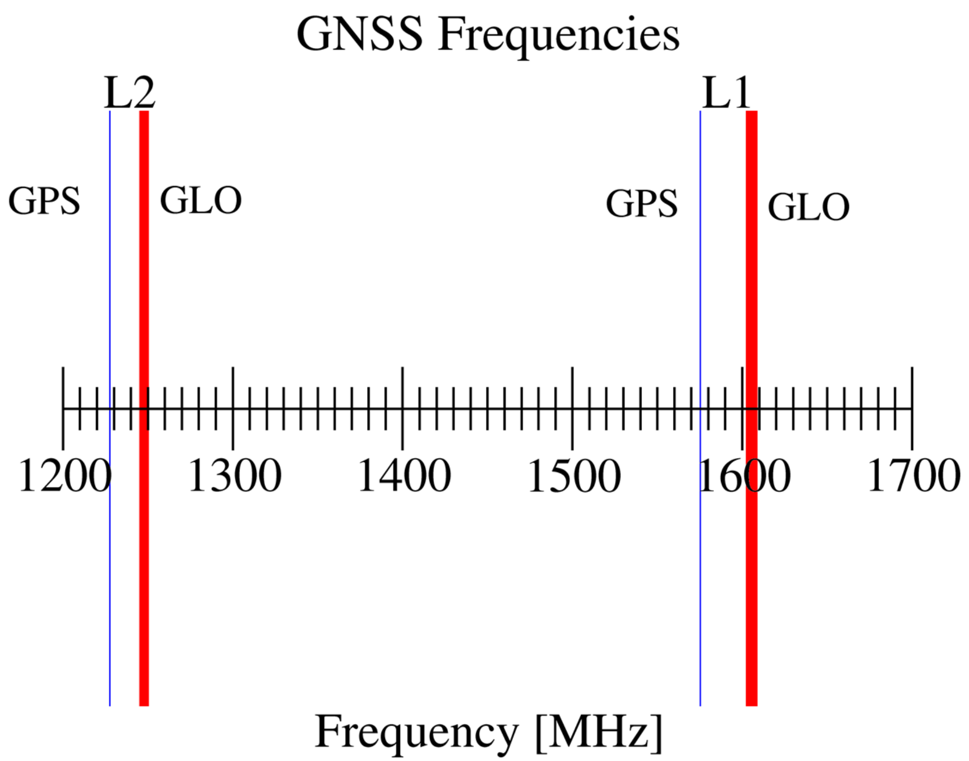


absolute antenna calibration



Calibration of GLONASS PCV

- GLONASS has **different frequencies** for **each satellite**
- need for frequency dependent GLO PCV
  - **determination of DeltaPCV** (change of PCV with frequency)
  - metric PCV obtained from combination of GPS PCV und GLO DeltaPCV
  - **GLO PCV can be extrapolated** to any other GLO frequencies (ie reference frequency is k=0)



Combine absolute GPS PCV + GLO DeltaPCV

- GLO DeltaPCV [m/25.0 MHz]

- **GPS PCV plus GLO frequency difference * GLO DeltaPCV**

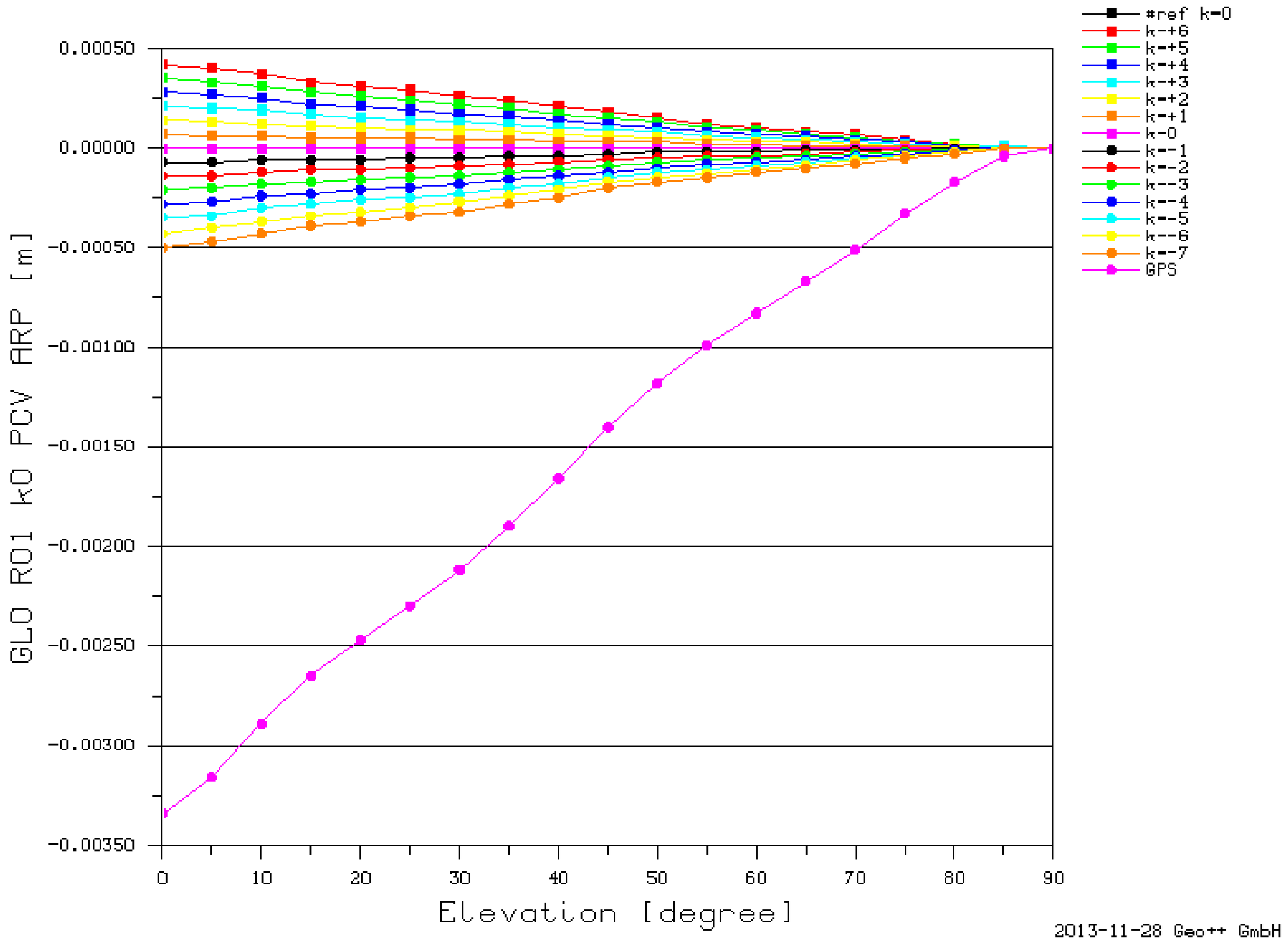
  - GLO_PCV_L1 [m] = GPS_PCV_L1 +
    ((1602.0 + channel_number * 0.5625) - 1575.42) / 25.0 * GLO_DeltaPCV_L1

  - GLO_PCV_L2 [m] = GPS_PCV_L2 +
    ((1246.0 + channel_number * 0.4375) - 1227.60) / 25.0 * GLO_DeltaPCV_L2

Calibration of GLONASS PCV

- **frequency dependent GLO PCV**
- converted to metric PCV
- frequency channel **k= -7 … +6**
- **comparison of dPCV** ,
  reference is PCV for k=0
- antenna chosen for example has large DeltaPCV
- magnitude in dPCV difference

  GLO L1/L2 Frequencies
  about 0.5 … 1.0 mm
- difference compared to GPS up to several mm



example for GLO L1 PCV JAV_RINGANT_G3T NONE

GNSS Antenna Calibration

- Geo++ GNPCV systems
- robot-based absolute GNSS antenna field calibration
- development by **Geo++** in cooperation with
  Institut für Erdmessung, **Universität, Hannover**
- **marketing and enhancement/development**
  through Geo++ since 2000
- in total six working Geo++ GNPCV systems
  - 2000 Geo++, **Garbsen** , Germany (to be retired)
  - 2000 ife, **Hannover** , Germany
  - 2005 SenB, Berlin, Germany (retired)
  - 2009 Geo++, **Garbsen** , Germany
  - 2012 GSA, Canberra, **Australia**
  - 2013 SenB, **Berlin** , Germany
  - 2018 Geo++, **Garbsen** , Germany (to be setup)

three robot-test, Mai 2012, Geo++ Garbsen

ife	Institut für Erdmessung, Universität Hannover, Germany
SenB	Senatsverwaltung für Stadtentwicklung Berlin, Germany
GSA	Geoscience Australia, Canberra, Australia

Repeatability of Phase Offsets and Variations

- repeatability of absolute PCV antenna calibration with robot
- **three different** GNPCV **robots**

robot	operated
Geo++	in Garbsen
ife	in Hannover
Berlin	tested in Garbsen

- **individual** ASH700936D_M **antenna** calibrated on

robot	date of PCV calibration
Geo++	2005-08-08
Berlin	2006-02-15
ife	2006-01-14

ife Institut für Erdmessung, Universität Hannover, Germany
Berlin Senatsverwaltung für Stadtentwicklung Berlin, Germany

Repeatability of Phase Offsets and Variations

L0 GPS difference of PCV

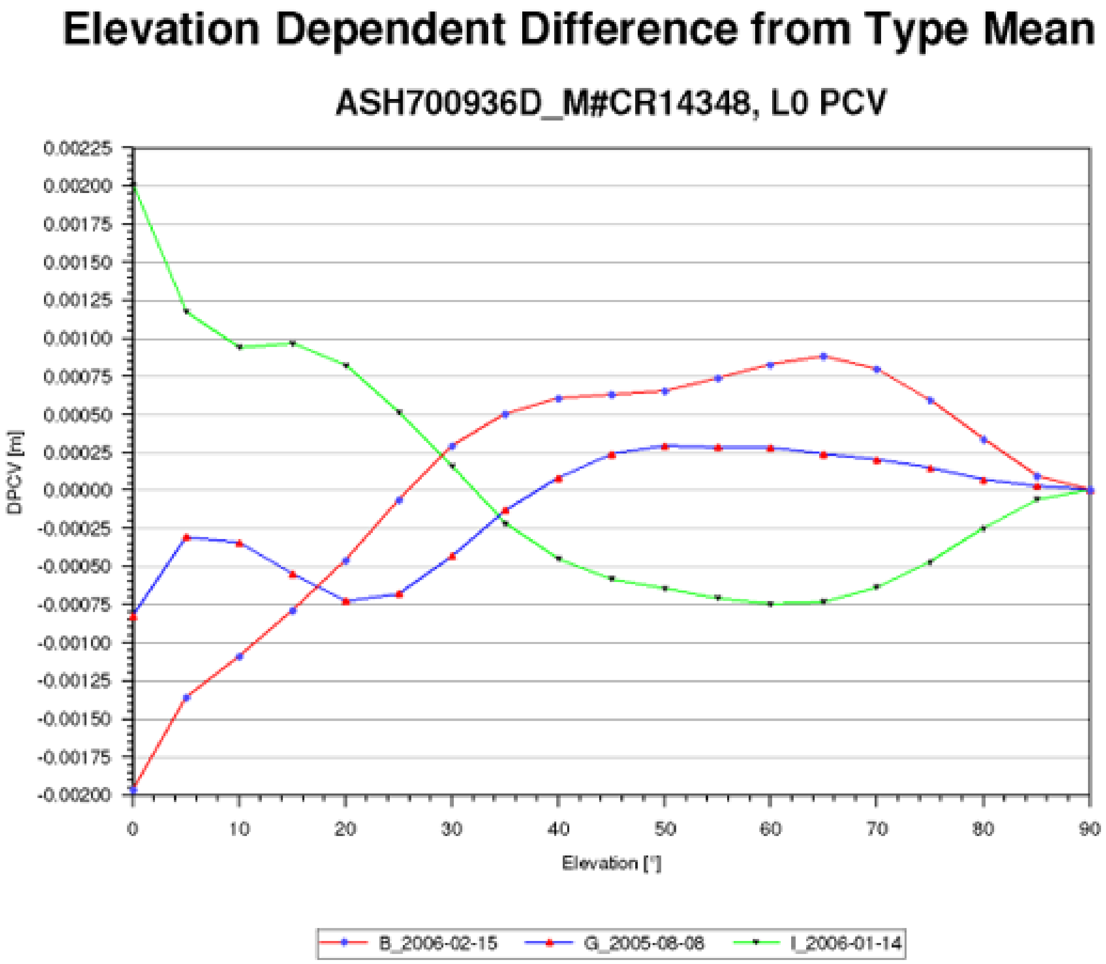
- individual ASH700936D_M antenna
- three different robots
- **ionospheric free signal**
- magnitude PCV differences

L0 < 1 mm

above 10 deg

- rule-of-thumb:

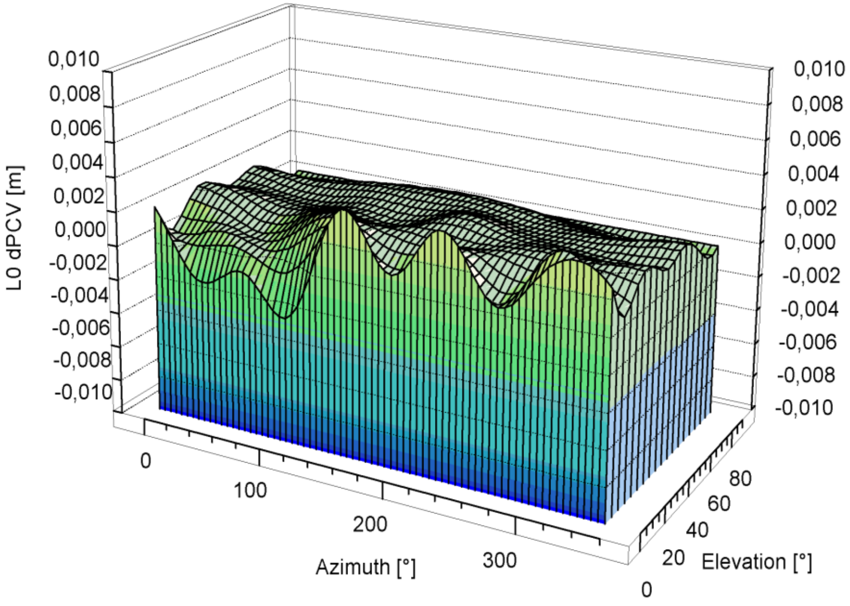
L0 factor 3 worse than original signal



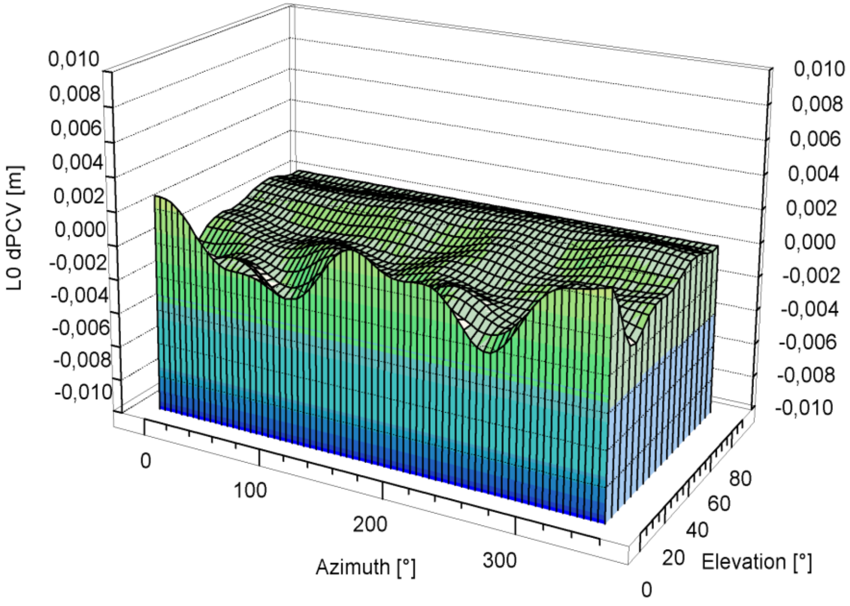
Repeatability Individual Antenna

Repeatability after 2 Years

- **geodetic antenna** ASH700936D_M SNOW
- **differences L0 PCV: average 1-2 mm**
- maximum at horizon about 4 mm



after 2 months

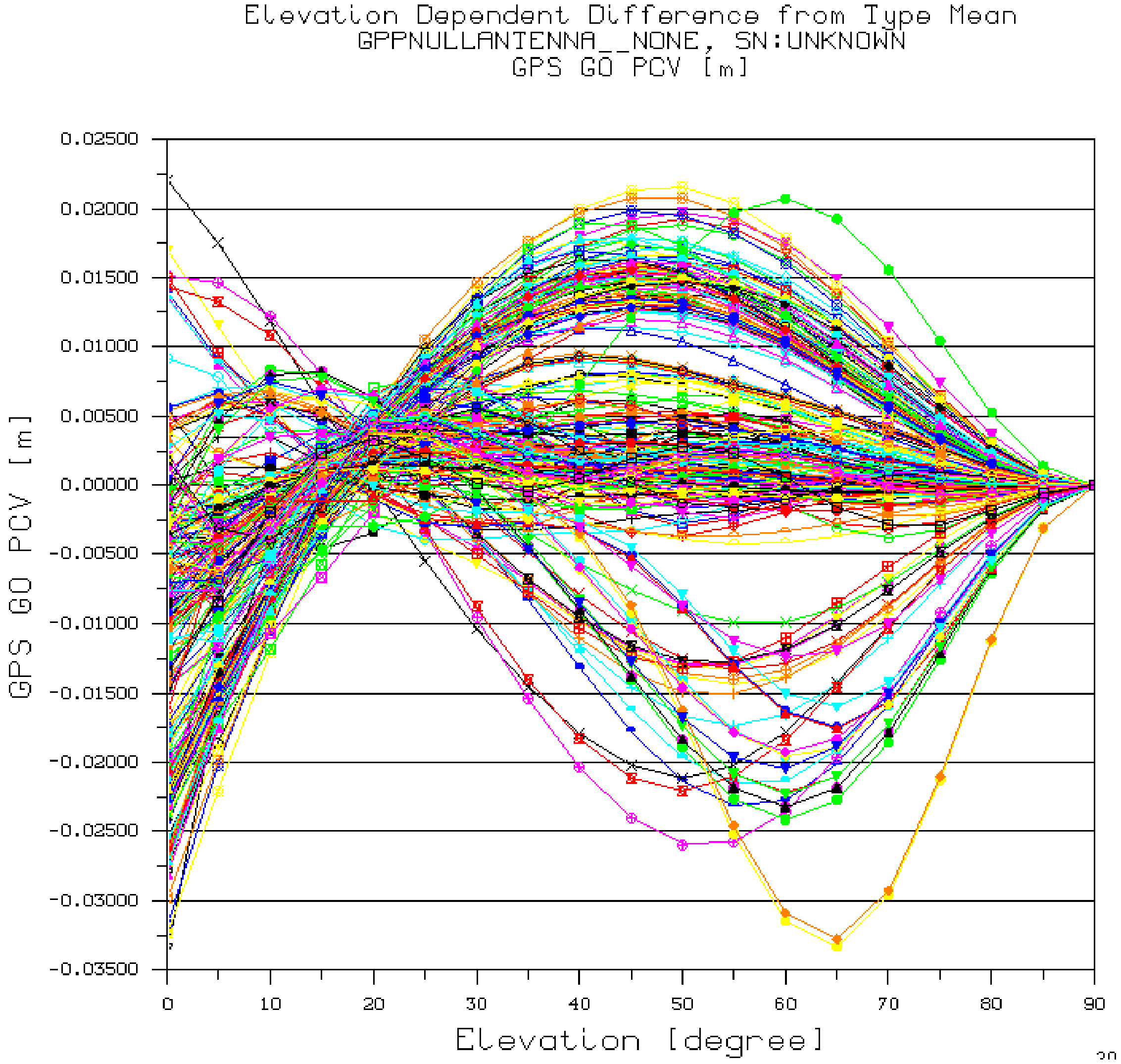


after 26 months

Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

GNSS Antenna Calibration

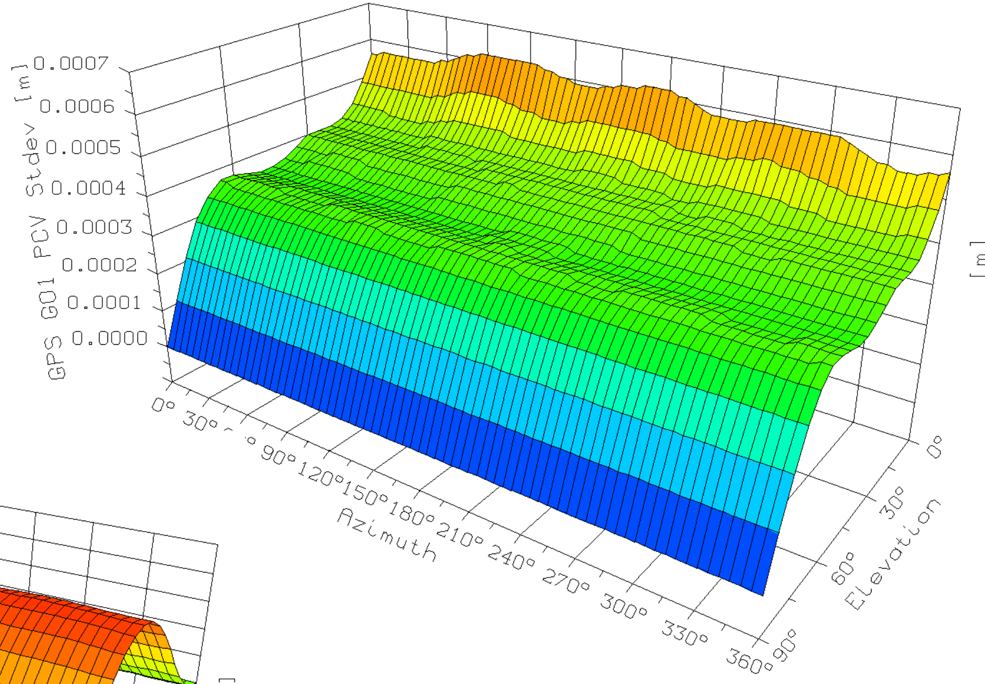
- **phase variation** (PCV without offset) for different antenna types
- 266 antenna types
- Geo++ GNPCVDB database
- **GPS L0** signal
- PCV **difference to GPPNULLANTENNA**
- magnitude of PCV
  - **up to several cm**
  - in high elevations

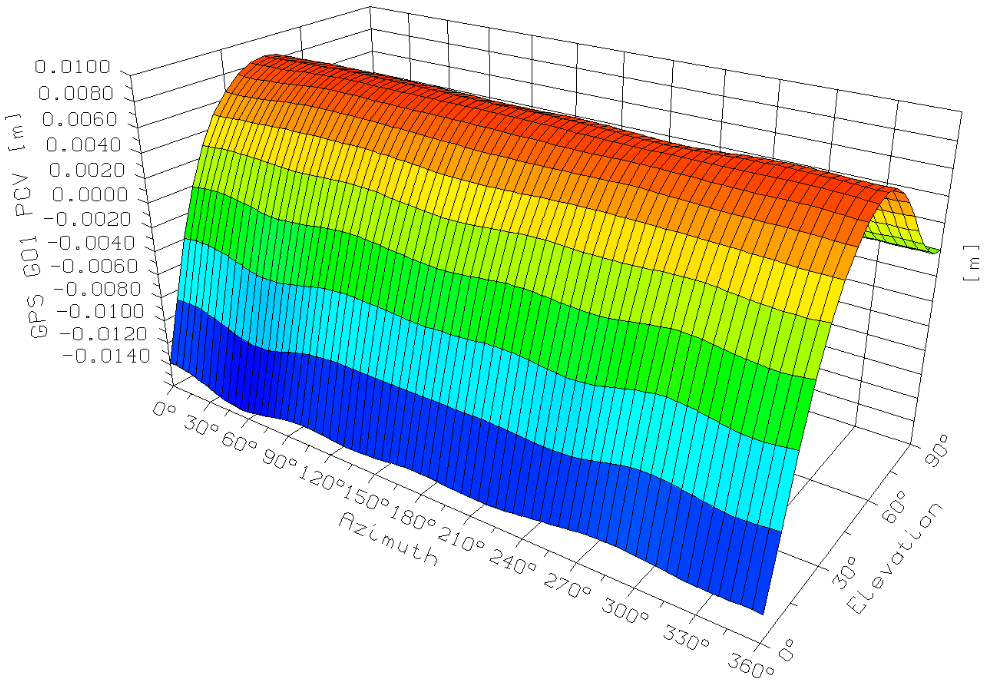


L0 ionospheric free signal rule-of thumb
L0 effects larger by factor of 3 than original signals (L1, L2)

Absolute GPS L1 PCV Pattern

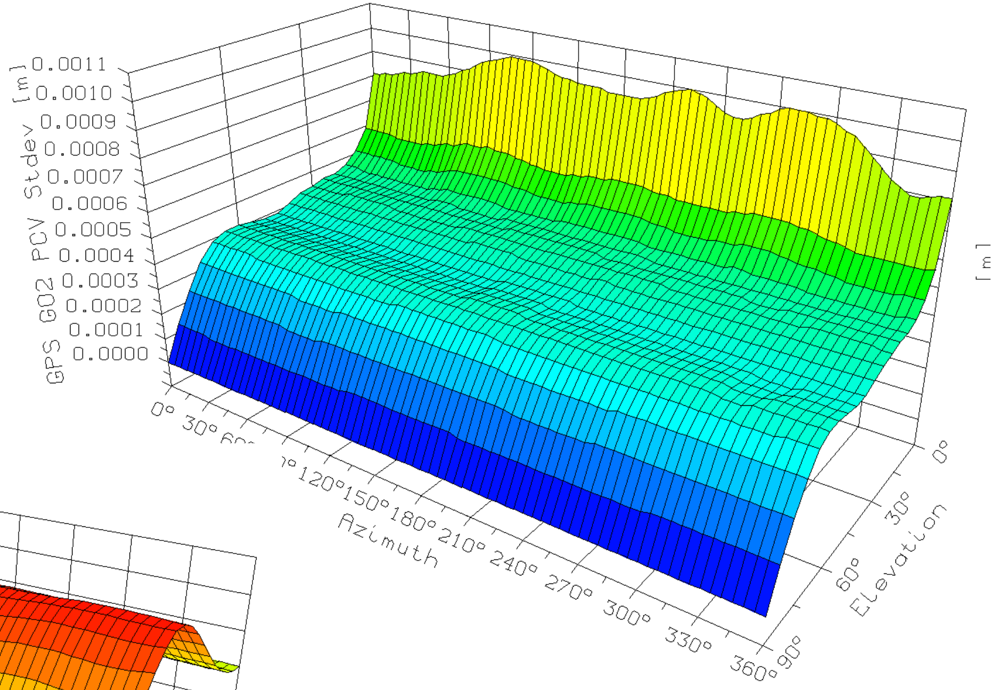
- **geodetic DM-type antenna**
- TRM59800_00   NONE
- PCV without offset
- L1 PCV
  -14 ... 10 mm
- stdev (individual)
  0.1 ... 0.4 mm

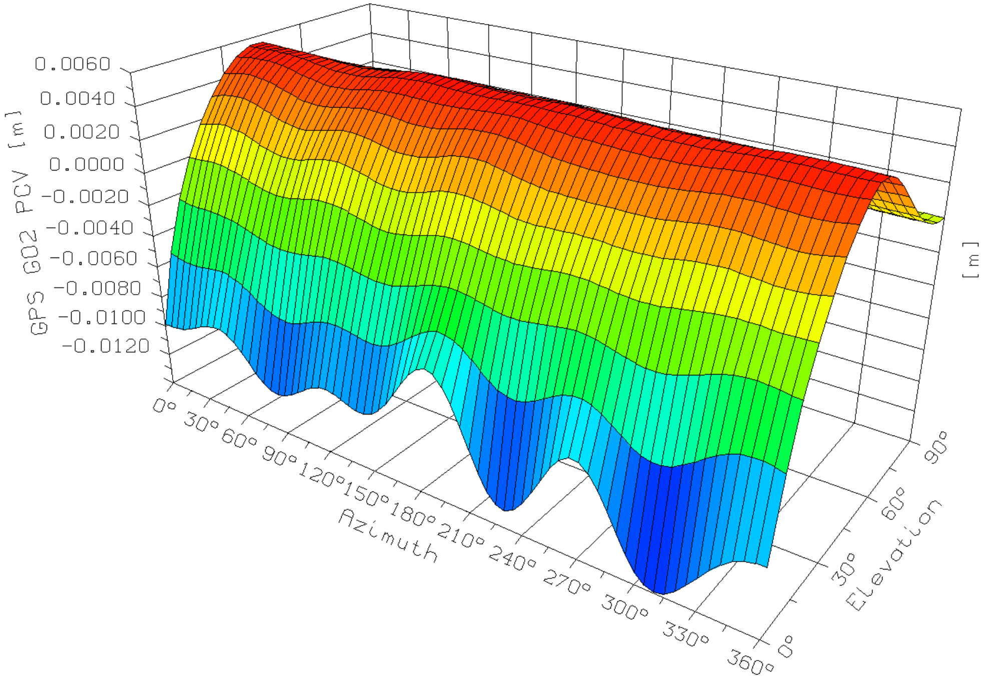




Absolute GPS L2 PCV Pattern

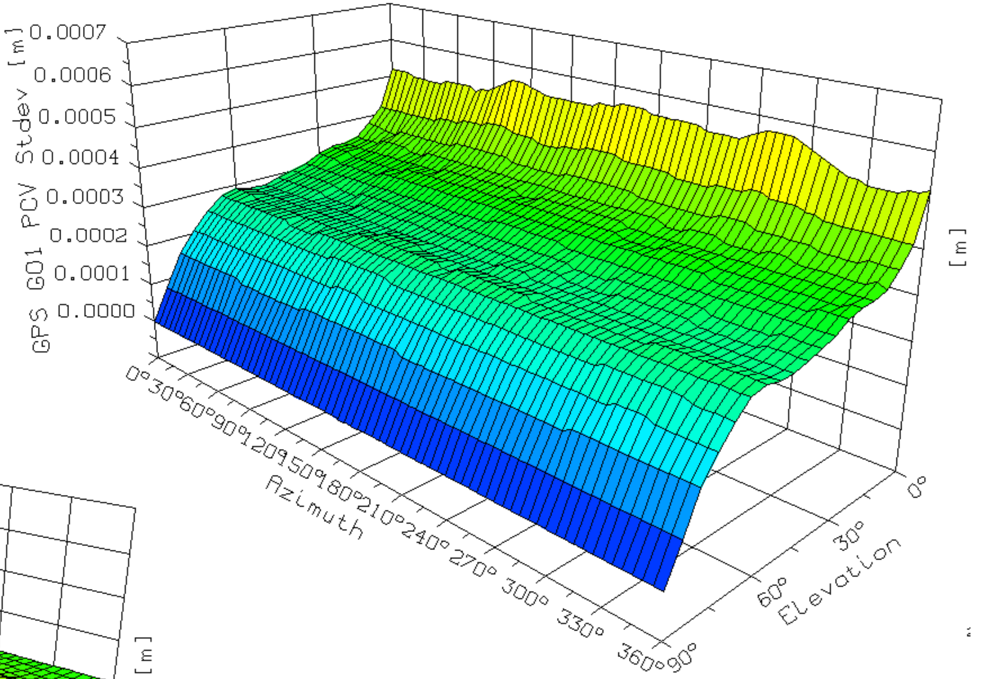
- **geodetic DM-type antenna**
- TRM59800_00 NONE
- PCV without offset
- L2 PCV
  -12 ... 5 mm
- stdev (individual)
  0.1 ... 0.4 mm

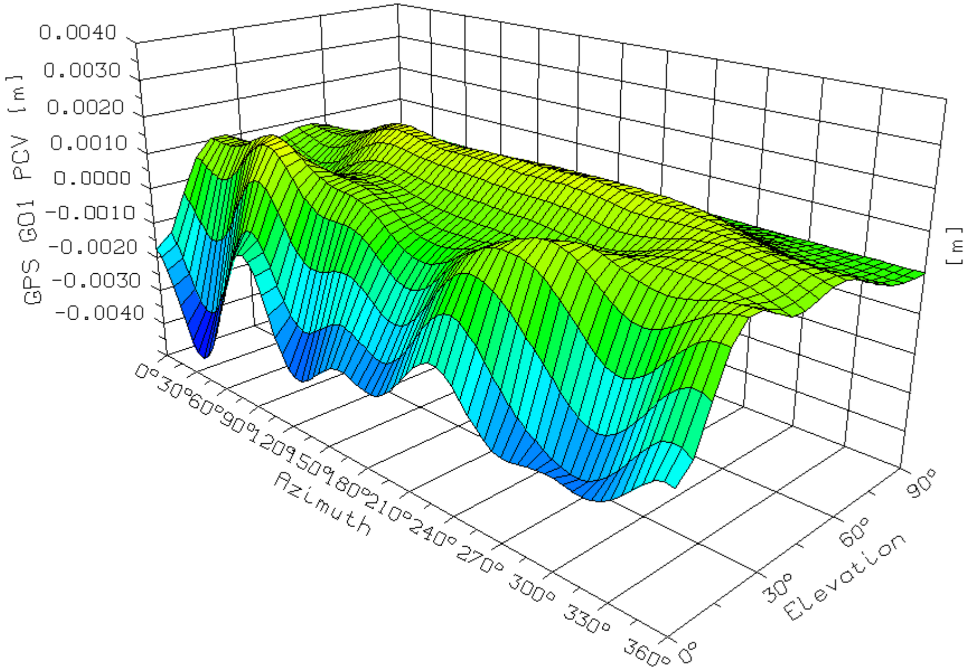




Absolute GPS L1 PCV and Standard Deviation

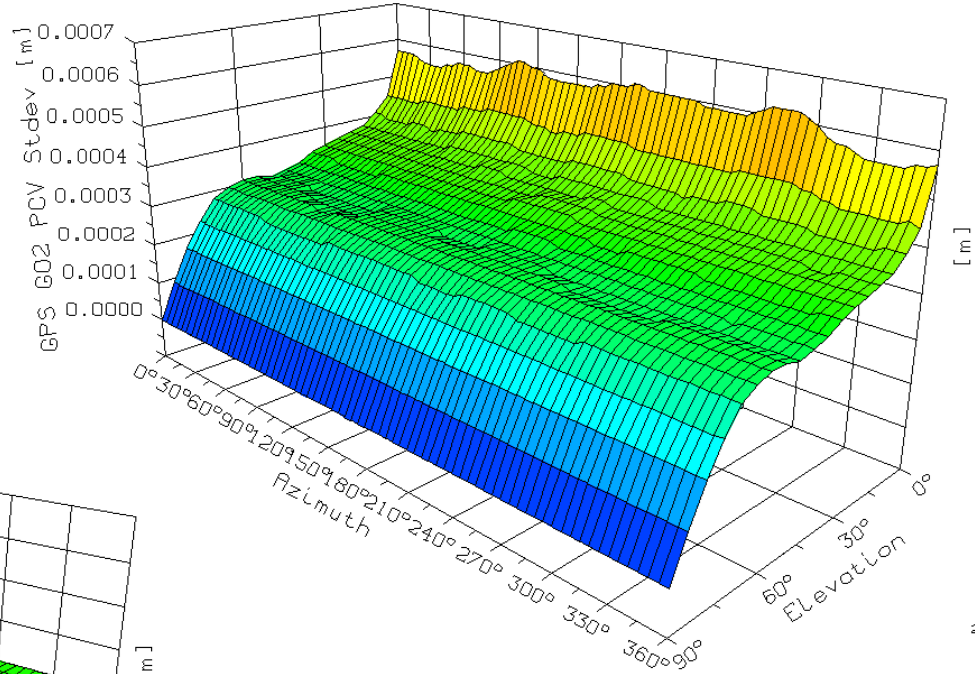
- **rover antenna**
- CHCX91+S NONE
- PCV without offset
- GPS L1 PCV
  -4 ... +2 mm
- stdev (type mean)
  0.1 ... 0.4 mm

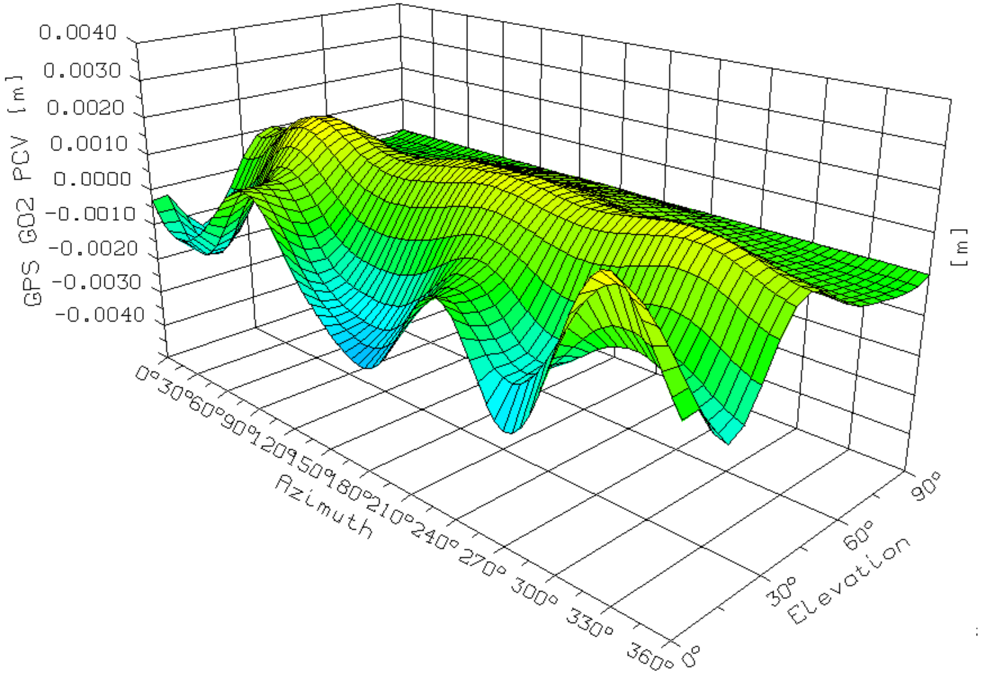




Absolute GPS L2 PCV and Standard Deviation

- **rover antenna**
- CHCX91+S NONE
- PCV without offset
- GPS L2 PCV
  -4 ... +2 mm
- stdev (type mean)
  0.1 ... 0.4 mm

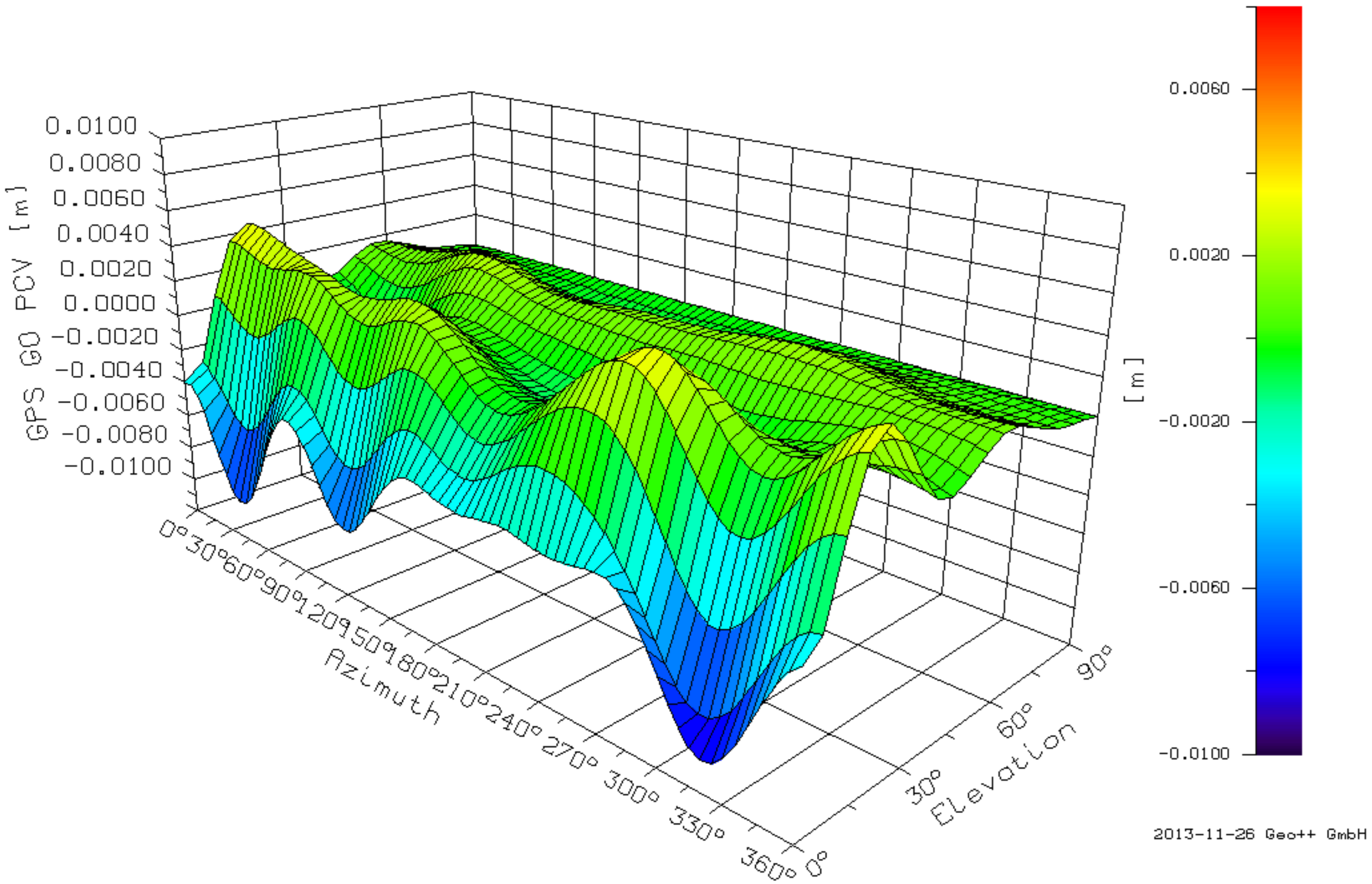




Absolute GPS L0 PCV

- **rover antenna**
- CHCX91+S NONE
- PCV without offset
- GPS L0 PCV

  -10 ... +4 mm



Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

- GNSS Antenna Correction (1)
- Some Details on absolute PCV Field Calibration
- GNSS Antenna Correction (2)
- Insight from Series of GNSS Antenna Calibrations
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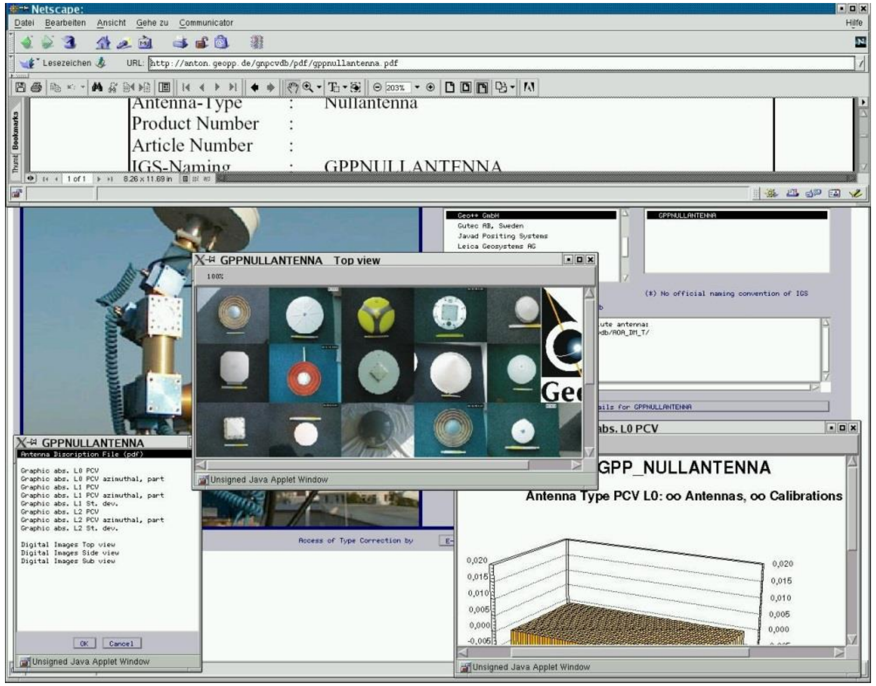
- Excursion - GNSS Satellite Antenna
- Excursion - Historical Review
- Summary/Outlook

GNSS Antenna Calibration - Geo++ GNPCVDB Database

- **absolute PCV type means**
- type means computed from several individually robot-based calibrated antennas
- rigorous adjustment using the complete variance-covariance matrix of individual calibrations
- November 2018
  - 334 different antenna types
  - 2705 / **7718** individual GPS antennas / **calibrations**
  - 1316 / **3679** individual GPS+GLO antennas/ **calibrations**



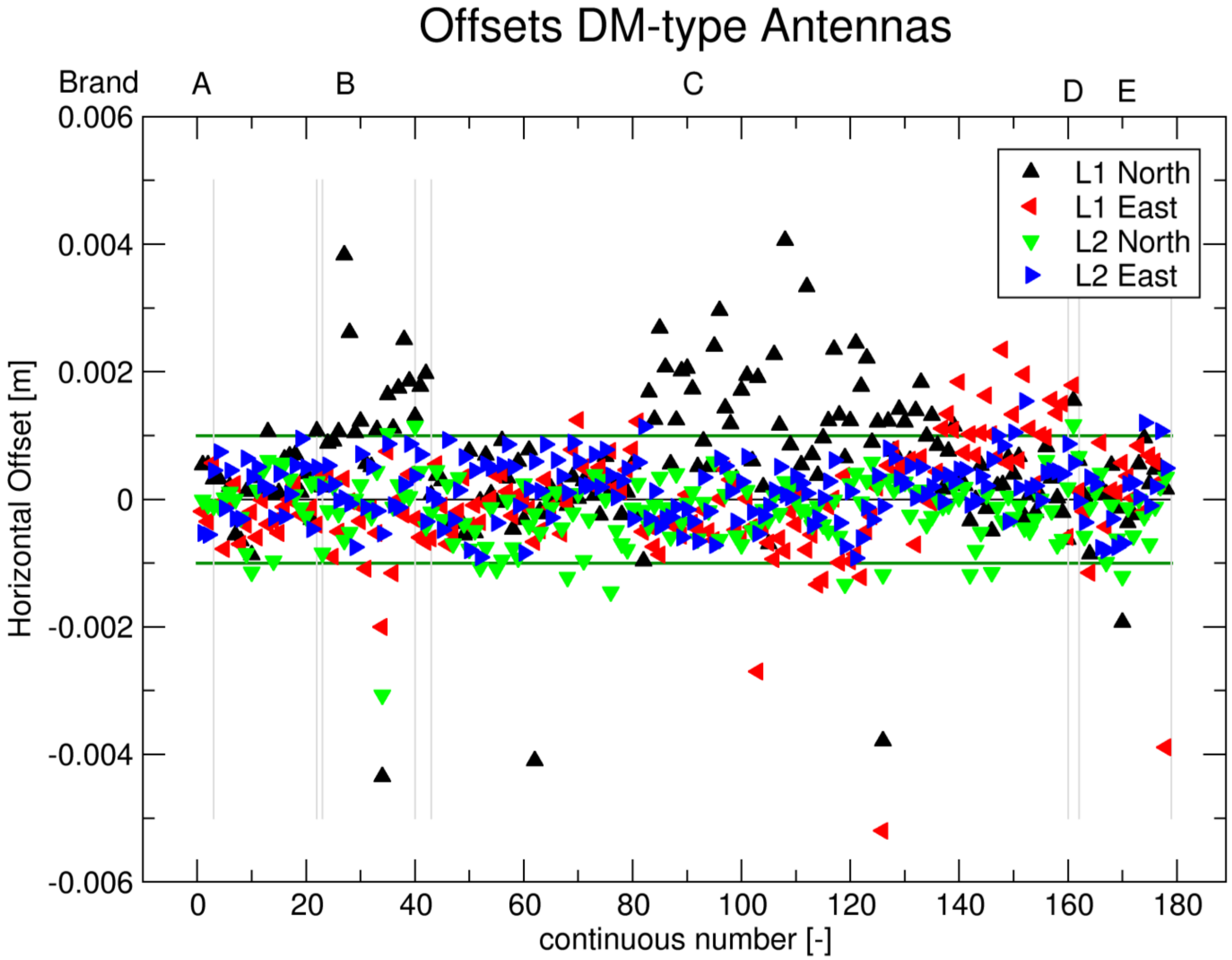
- **free access to information** on PCV pattern (graphics, **ARP-** und **NRP** definition, etc.)
- certain type means are provided to IGS/EPN (see eg **IGS igs14.atx**)
- license for actual access to absolute PCV (numerical values of PCV)
- http://gnpcvdb.geopp.de/

Offset Analysis DM-type Choke Ring Antennas

horizontal offsets

- 5 **different brands**
- 8 **DM-type antennas**
- with or without radome not distinguished
- **remark**: offsets not suited to describe PCV,

  however, offsets are also azimuthal PCV
- obviously
  - **outliers**
  - significant **changes in model series**



Offset Analysis DM-type Choke Ring Antennas

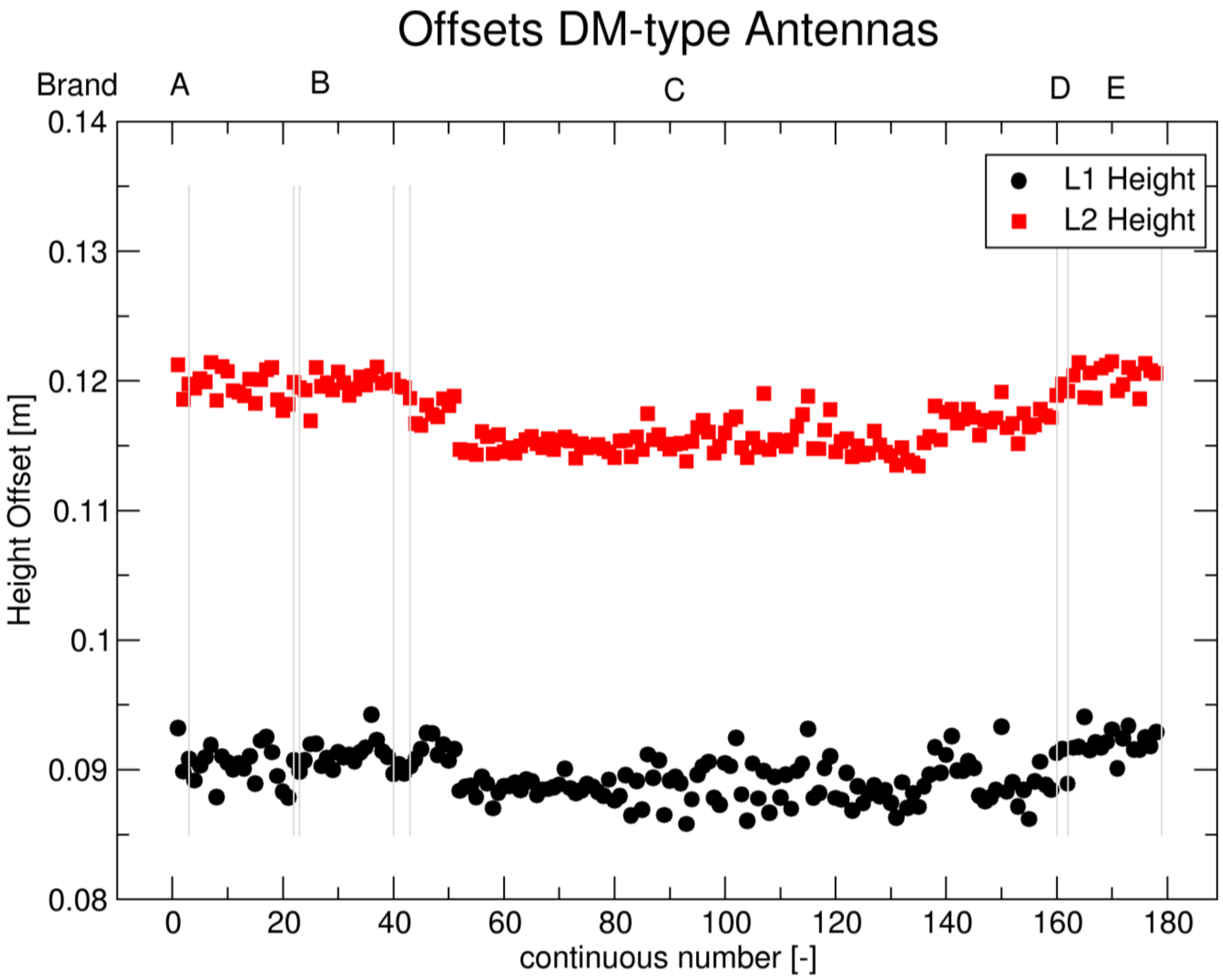
height offset

- dimension of antenna basically identical
- height offset from calibration much weaker than horizontal offsets

- standard deviation

  over all antennas about 2 mm
- different height level

  for different model type

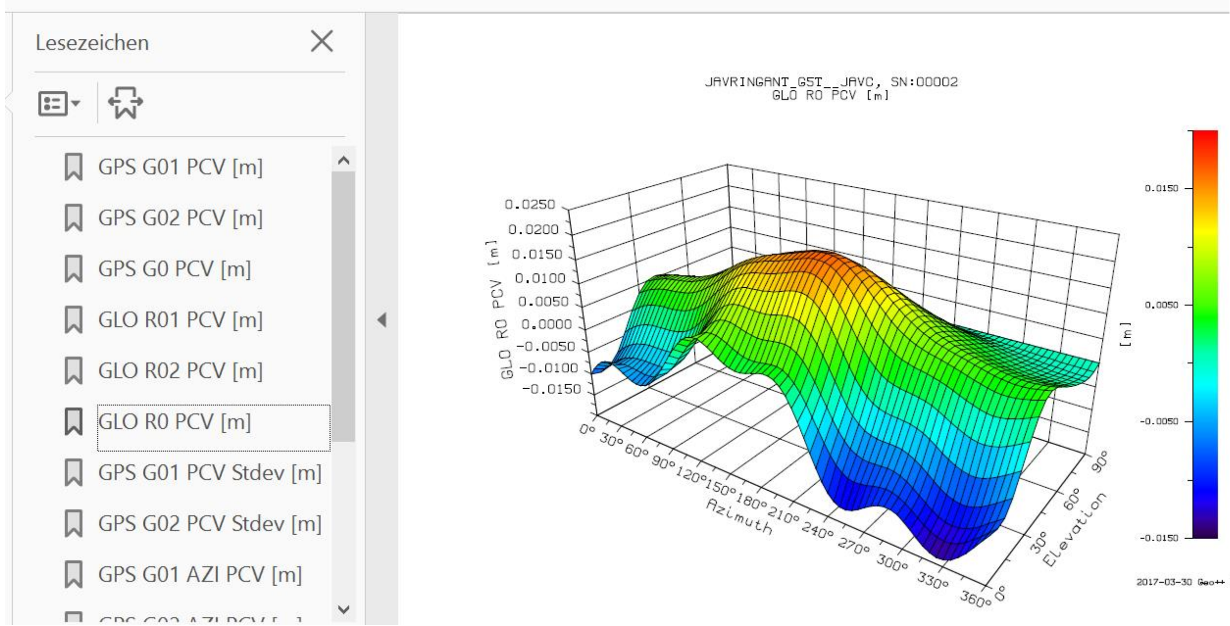


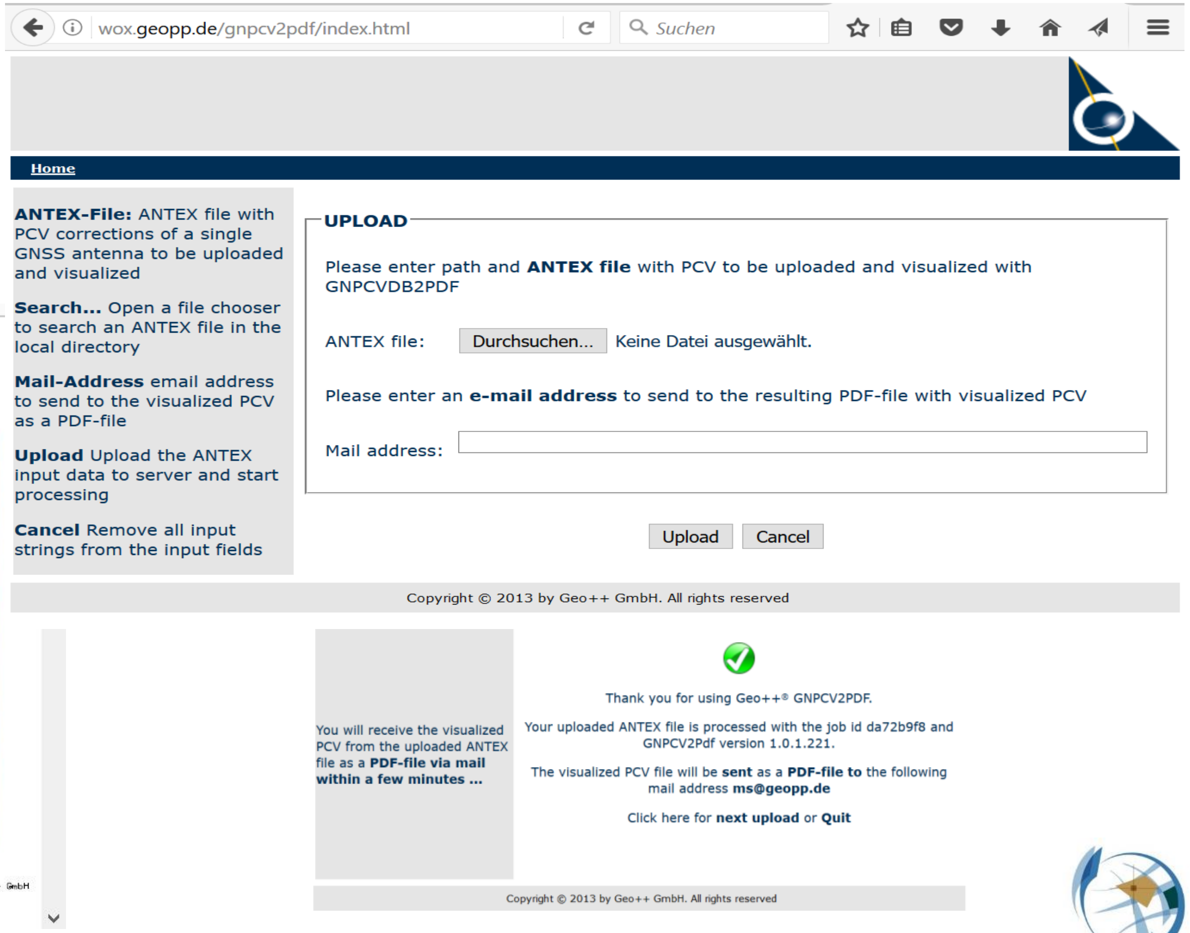
Insight from Series of GNSS Antenna Calibrations

- experiences from numerous antenna calibration
- one can observe
  - individual characteristics of antenna
  - outliers compared to type mean
  - changes in model series
  - modification of antenna model
  - assembling errors
- **recommendation** for precise application
  - **individual calibration** of antenna

You want to see your PCV pattern?

- ANTEX file with one single antenna can be visualized
- Geo++ GNPCV2PDF accessible at
- http://wox.geopp.de/gnpcv2pdf/index.html
- a pdf-file is send to you by e-mail





Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

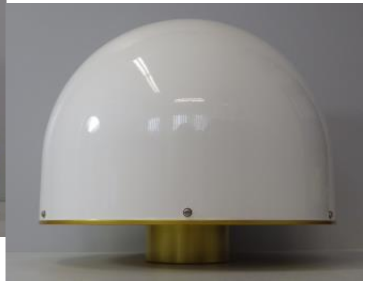
GNSS Antenna Group Delay Variations

- DM-type geodetic chokering antennas
  - TRM159800.00 SCIS
  - TRM159800.00 NONE
  - TRM59800.00 NONE
  - JAVRINGANT_DM SCIS
- geodetic chokering antennas
  - HXCCGX601A HXCS
  - HXCCG7601A HXCG
- geodetic antenna
  - TRM41249.00 SCIT
- rover antenna
  - SOKGCX3 NONE
  - IGAIG8 NONE



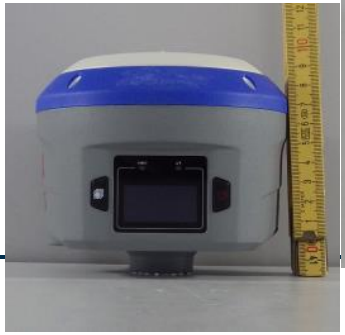
geodetic chokering antennas DM-type

geodetic chokering antennas

geodetic antenna with SCIT

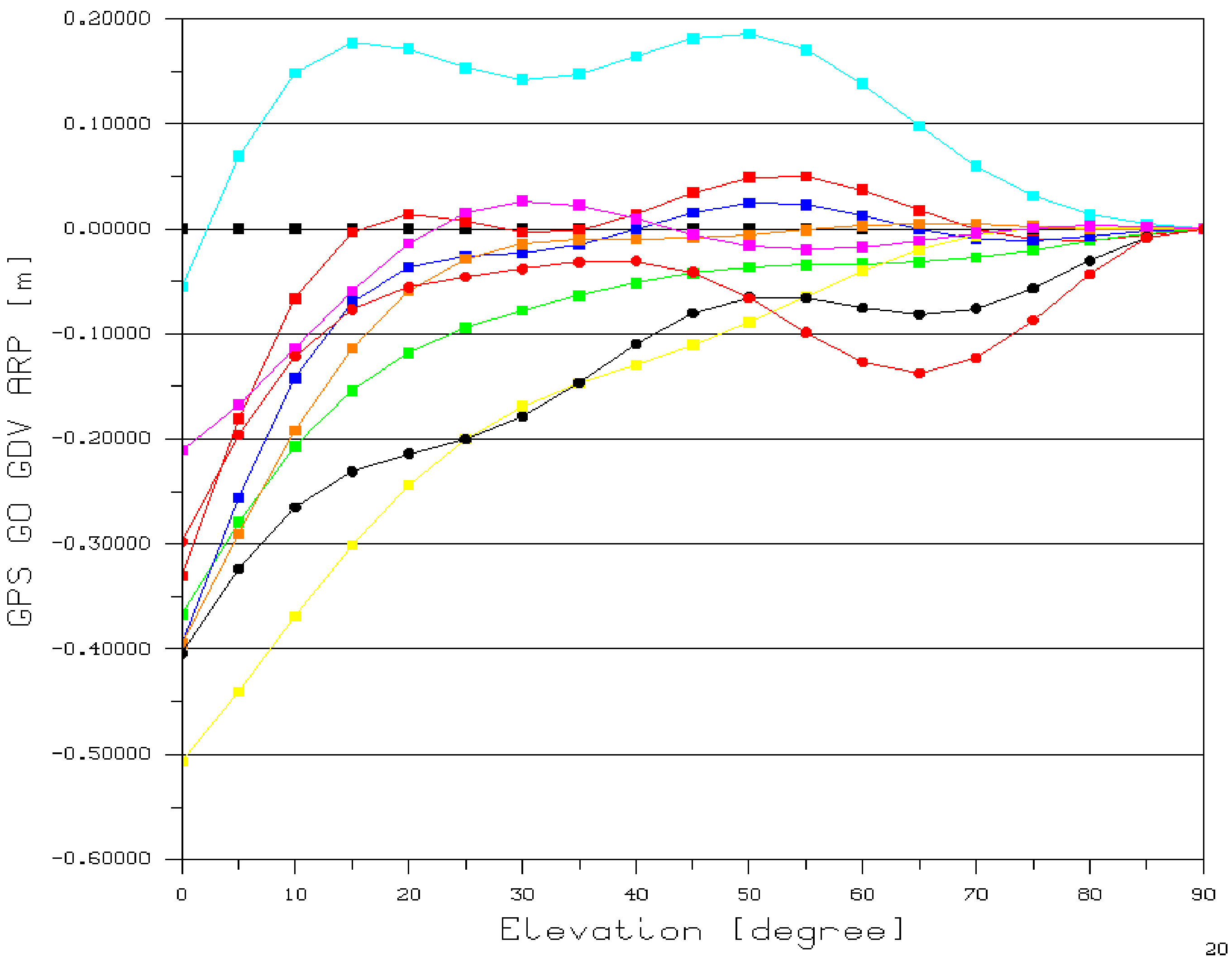
rover antennas

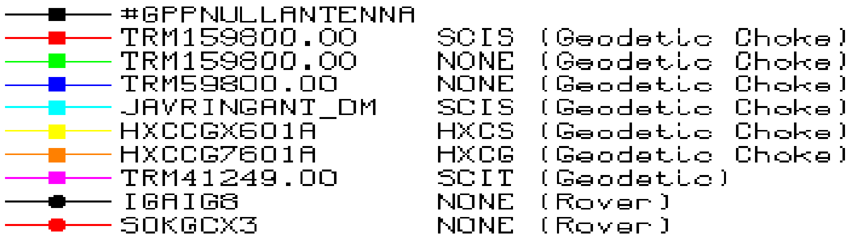



DM Dorne Margolin element

GNSS Antenna Group Delay Variations

- examples of some **GDV** pattern
  - geodetic choke ring antennas with and without radome
  - geodetic antenna with radome
  - rover antennas
- **significant effects** for code sensitive applications (eg PPP utilizing Melbourne-Wübbena linear combination)





Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

Station Dependent Errors

- benefits separating of individual error components
- PCV and multipath effects are most important station dependent errors

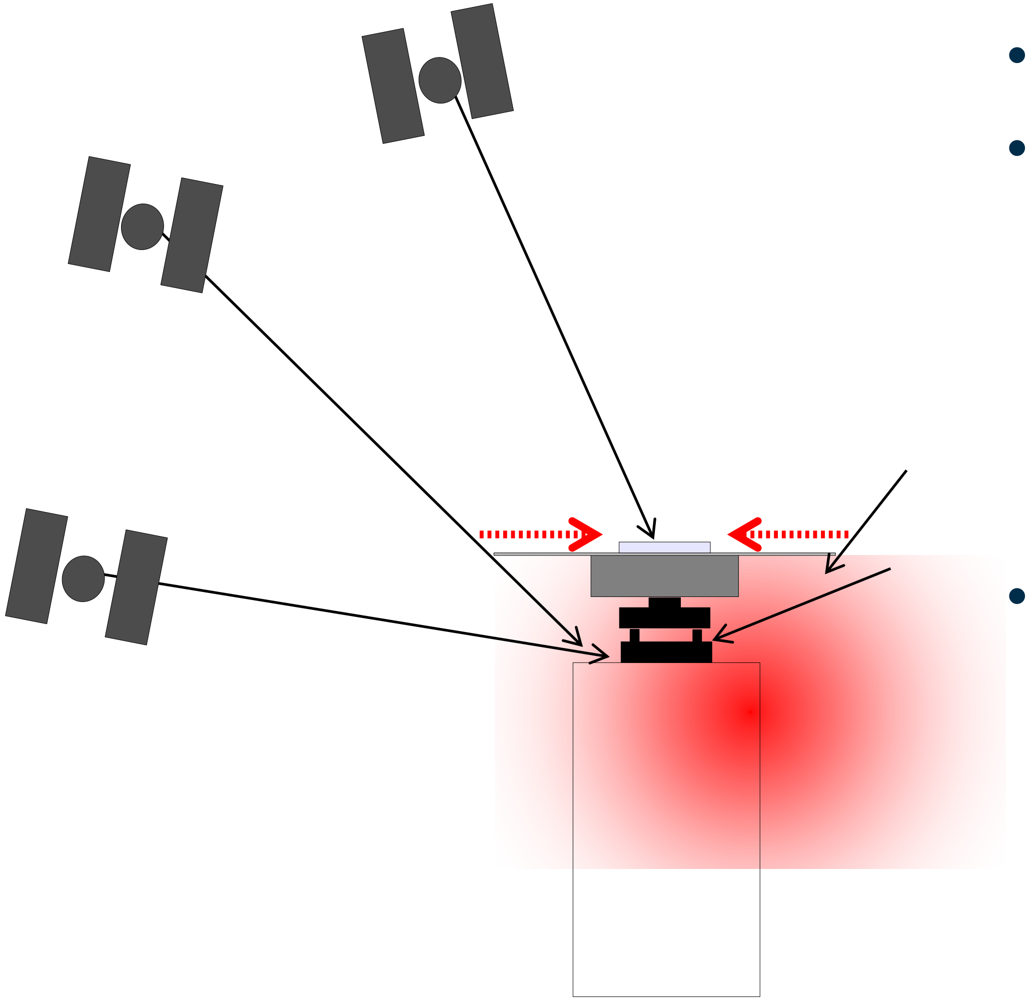
$$dS = PCV + MP$$

PCV	=>	absolute GNSS antenna calibration
multipath	=>	difficult to calibrate, therefore model highly variable total MP in an operational procedure

- strategy to **separate near-field (NF) and far-field (FF) multipath**

$$dS = PCV + MP_{NF} + MP_{FF}$$

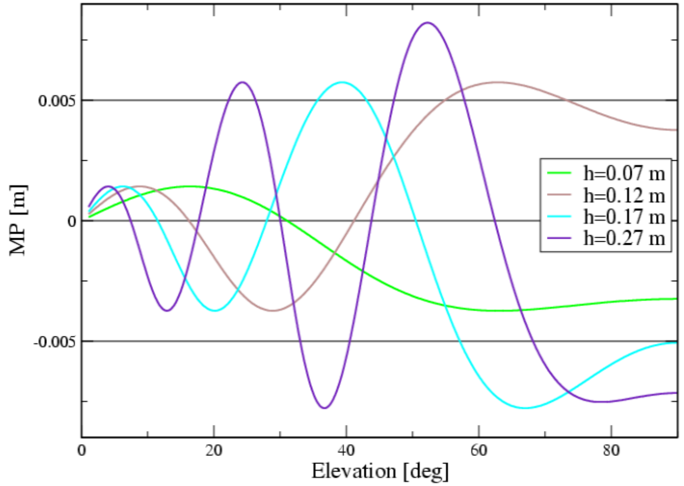
Near-Field Multipath: Causes

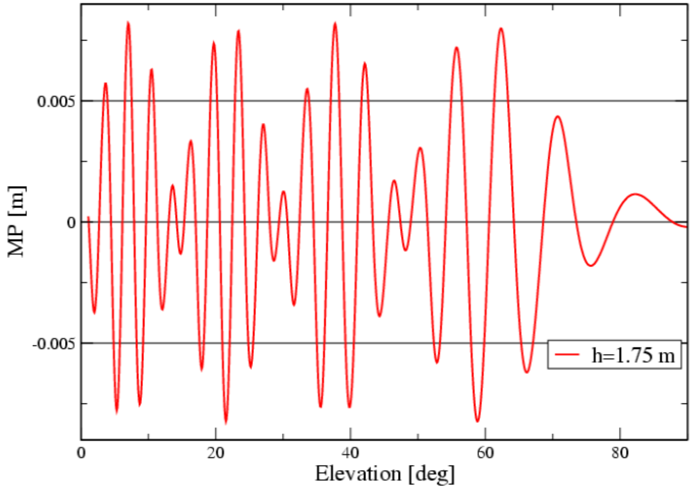


- **antenna near-field** depends on
- antenna **type** (plus radome construction, ...)
    - **mount/setup** (tripod, tribrach, adaption, ...)
    - station **environment** (pillar, roof, ...)
    - **weather** conditions (reflecting coefficient, snow, ...)
- effect on signals **due to**
    - **reflection**
    - **diffraction**
    - **imaging** / electro-magnetic inter-action

Near-Field Multipath: Theoretical Impact

- **horizontal reflector close to antenna** (pillar setup)
  - low multipath frequency
  - impact also in high elevation
  - **no averaging** over time, bias
  - **systematic positioning error**
- **typical setup of antenna** (tripod setup)
  - high multipath frequency
  - impact over complete elevation range, systematic effect
  - **averaging over time**





Station Dependent Errors: Different Treatments

	Error	Characteristic	Treatment
Antenna	PCV	elevation and azimuth dependent PCV and GDV	calibration of PCV and GDV using robot
Multipath	$MP_{near\text{-}field}$	long-periodic, systematic effect, bias	calibration of near-field effects using robot/ in-situ station calibration - or avoid
	$MP_{far\text{-}field}$	short-periodic, systematic effect	averaging over time, absolute station calibration or weighting (CN0), sidereal differences (GPS only) - or avoid

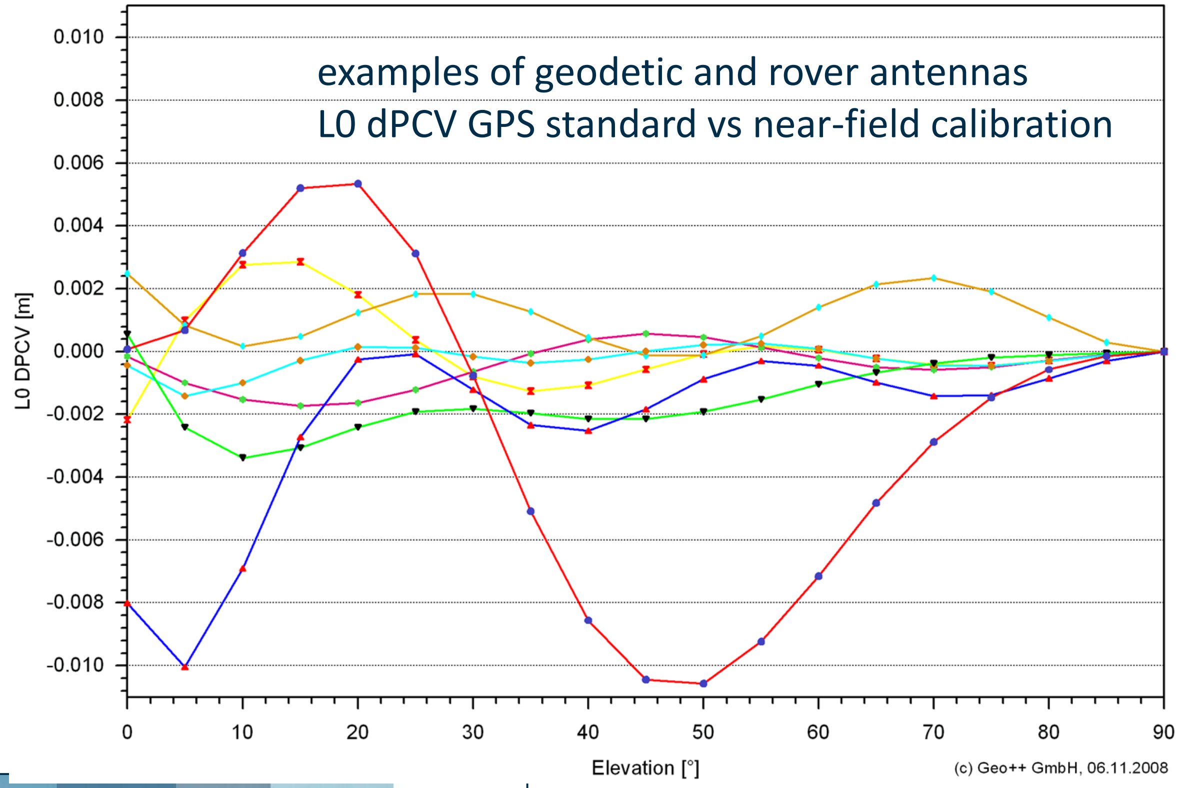
Near-Field Multipath: Robot Calibration

- **determination of near-field effect** with precise robot calibration
  - standard deviation 0.2 to 0.4 mm
  - repeatability 1 mm, except close to horizon
- **representative near-field environment** required
- **constant geometric relation** antenna/near-field despite movements of antenna
- calibration provides

  $PCV + MP_{NF}$
- **separation** obtained through **difference** of calibration **with/without near-field** environment and antenna

Near-Field Multipath Results

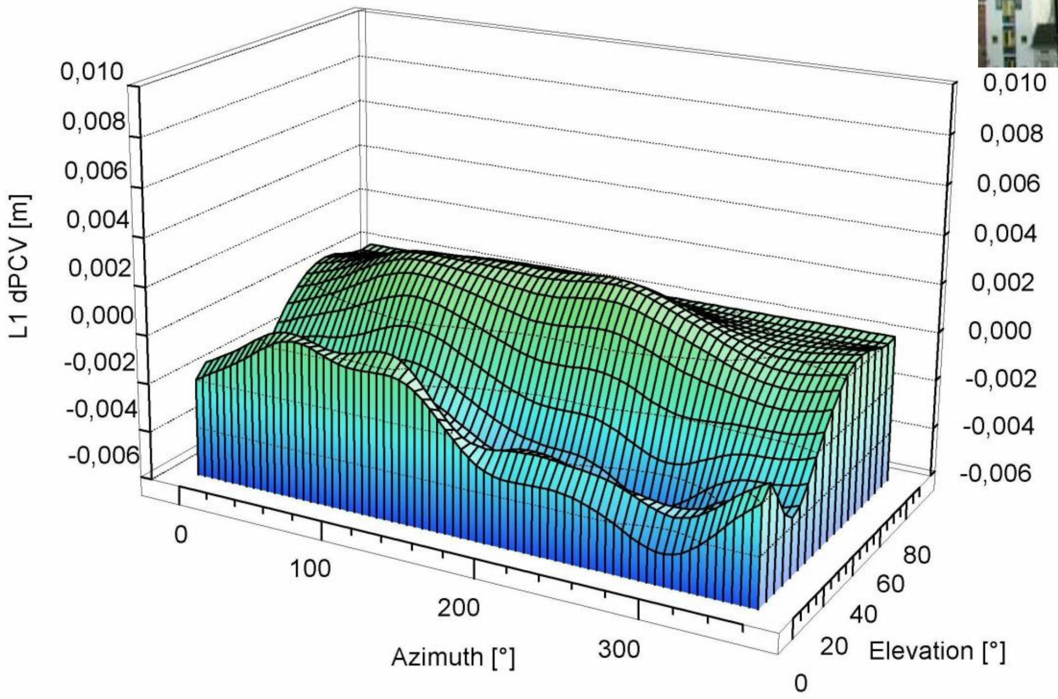
- **mm … cm PCV changes**
- but, amplification and
- dependency on
    - linear combination (L0)
    - tropospheric modeling
    - satellite constellation
    - elevation mask
    - …
- effect in position domain
- height much higher affected



1 2 3 4 5 6 7

Real Life Example from RTK Networking

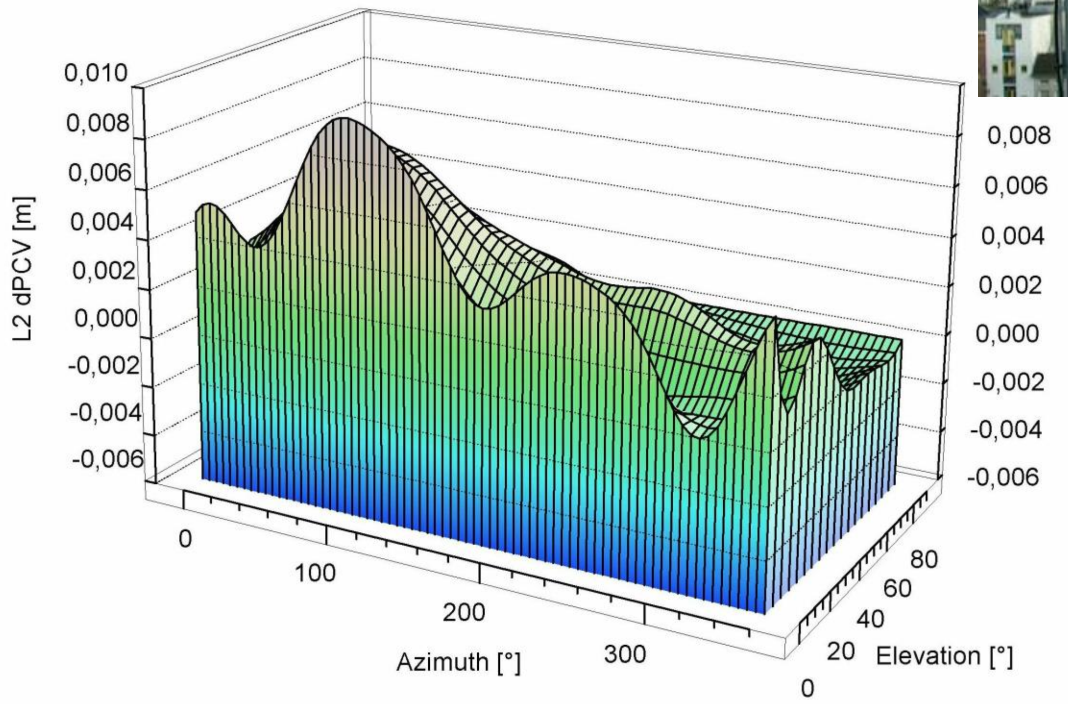
- TPSPG_A1 **GNSS rover antenna**
- **10 cm prism spacer** and special construction with two **ground planes ca. ∅ 14cm**
- target device for classical surveying
- **L1 PCV difference** against regular calibration
    - 10-30° elevation
    - mean ca. 3 mm maximum 6 mm
    - 40-70° elevation
    - mean ca. 1 mm maximum 2 mm



Real Life Example from RTK Networking

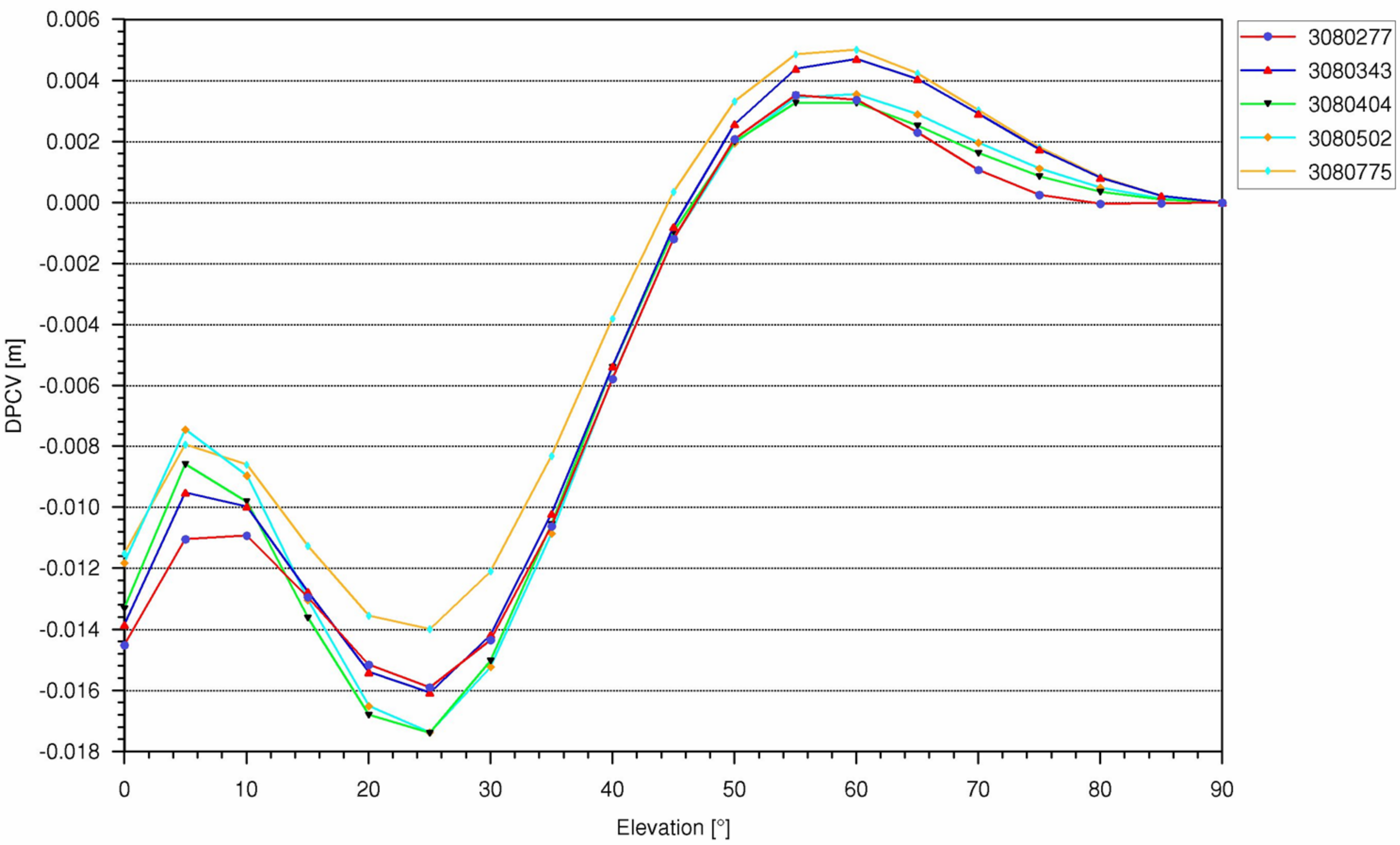
- TPSPG_A1 **GNSS rover antenna**
- **10 cm prism spacer** and special construction with two **ground planes ca. ∅ 14cm**
- target device for classical surveying
- **L2 PCV difference** against regular calibration
    - 10-30° elevation
    - mean ca. 4 mm maximum 8 mm

    - 40-70° elevation
    - mean ca. 1 mm maximum 4 mm

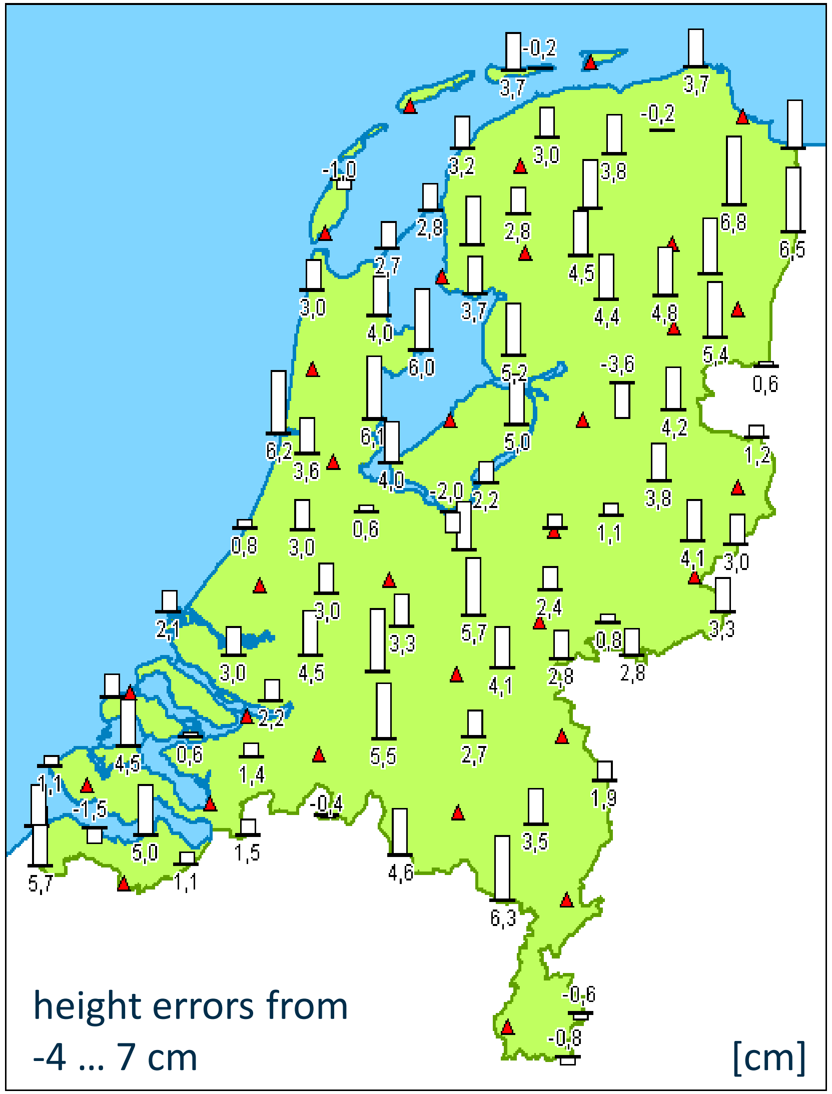


Real Life Example from RTK Networking

- **amplification** for L0 PCV
- L0 PCV differences agains
    - 10-30° elevation
    - maximum -18 mm
    - 40-70° elevation
    - maximum +5mm
- repeatability of five antenna constructions ca. 4 mm
- also individual PCV and near-field components of antennas present



Real Life Example from RTK Networking



- Kadaster, The Netherlands, 2006
- NETPOS **RTK Network** (31 stations)
- **81 control points** of Dutch network
- 10 RTK measurements with
  10 initializations each time
- **without near-field correction**
  - time and spatial dependent height errors
  - mean of **systematic height error** is 31 mm (81points)
- **with near-field correction**
  - **free of systematic height errors**
  - mean height difference is -2 mm (49 points)

GNSS Antenna Correction - Impact

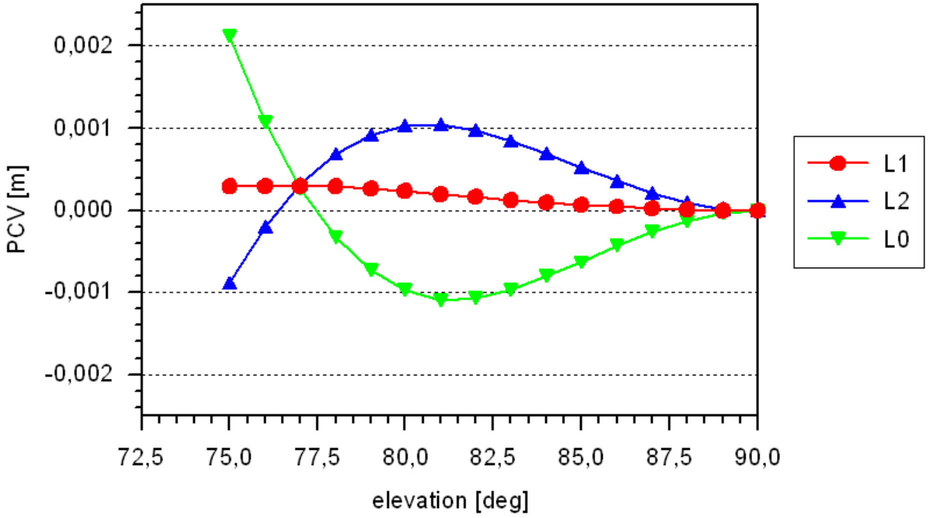
- **not rigorously corrected** GNSS **PCV** of reference station antenna may **cause positioning errors** for the user
- in general impact is transferable to any deficiency in GNSS antenna correction
- **mm in PCV** domain may cause **cm in position** domain errors
- cause are **time- and location-dependent amplifications** through
  - linear combination (L0)
  - inter-action troposphere modeling
  - satellite constellation
  - elevation mask
- **height** component **mainly affected**
- but also **potential effect** on **user** positioning algorithms

Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

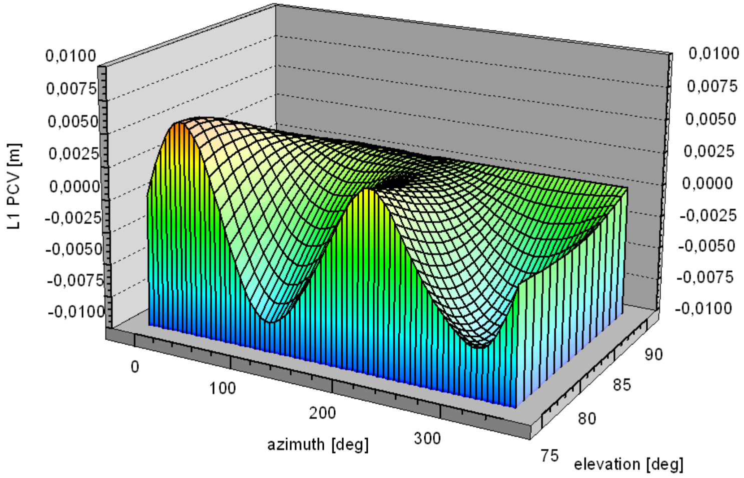
Excursion - GNSS Satellite Antenna

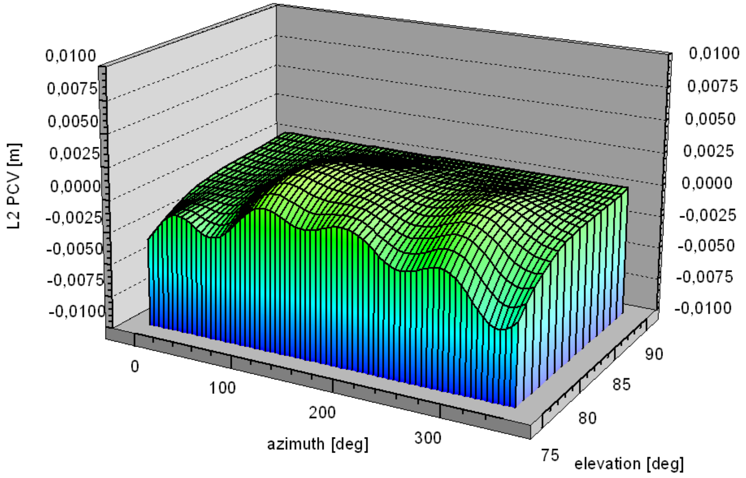
- **GPS Block II/IIA Satellite Antenna**
- 2008 cooperative project of **NGS, Boeing and Geo++**
- GPS Block II/IIA antenna with 14.4 kg, Ø 1.34 m
- small area of interest (**15° cone**), but data >30° used
- improved coverage due to robot
- estimation of **L1 and L2 PCV**
- **elevation and azimuth dependency**
- not affected by GNSS errors (eg ionosphere, troposphere, etc) due to short baseline
- currently offsets and pure elevation dependent PCV derived from global networks

GPS Block II/IIA Satellite Antenna



pure elevation dependent PCV



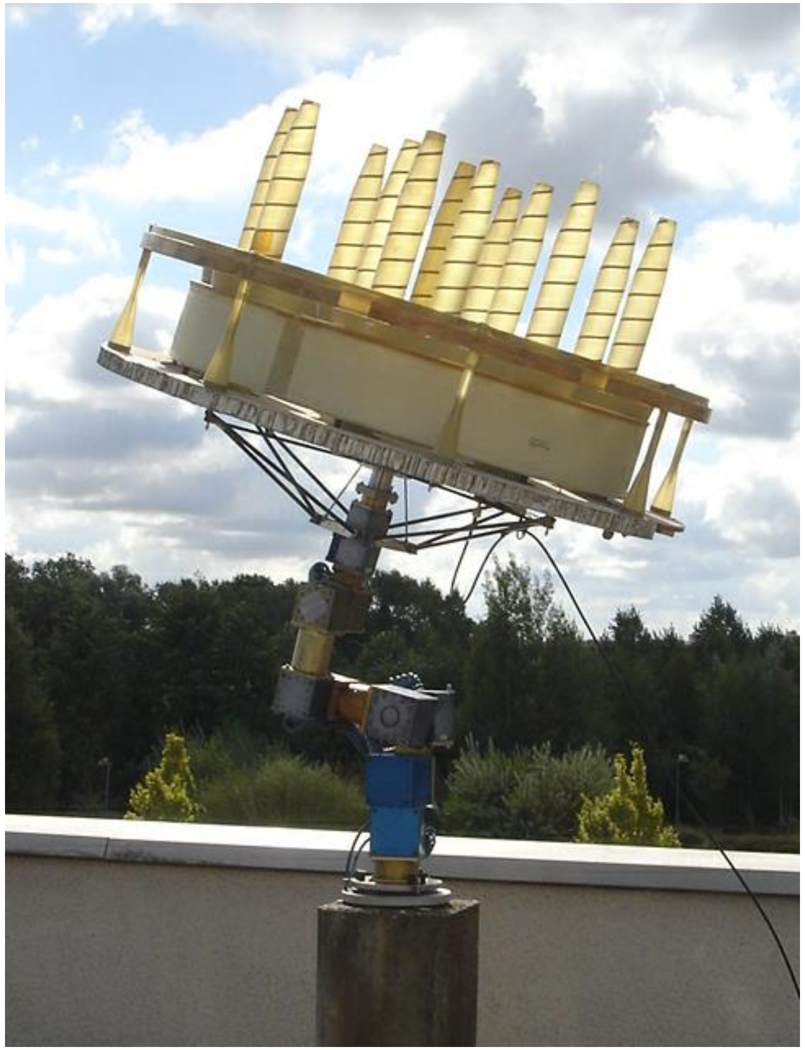


elevation and azimuth dependent PCV

- **mm magnitude** of
  pure elevation dependent **PCV**
- **azimuthal PCV** at 15° zenith distance range from
  -8 ... +6 mm for L1 PCV
  -4 ... +2 mm for L2 PCV

Calibration of GNSS Satellite Antenna

- demand for **consistency of absolute receiver PCV and satellite PCV**
- provides consistency for
  - station coordinates/terrestrial scale
  - orbit parameters
  - troposphere
  - ...
- **general GNSS performance improvement for certain applications**



Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

Development of Absolute PCV Field Calibration

driven by Geo++ mainly due to need for RTK network

- **siderial day differences** (**1992**), first PCV calibrations (1992-1993)
- close cooperation with IfE (since 1995)
- spherical harmonics PCV model, post-processing with GEONAP (1995)
- development of **antenna mounts** (**1996-2000**)
- absolute calibrations and detailed analysis (1995-1999)
- automated absolute PCV field calibration in real-time using robot (2000)
- **operational absolute PCV field calibration** (since **2000**)
- …

Development of Absolute PCV Field Calibration

- publication of absolute **PCV for AOAD/M_T** (**2000**)
- proposal of GPP_NULLANTENNA (2000)
- absolute PCV supplied for analysis/verification/use (2000-2001)
- Geo++ GNPCVDB antenna database (2001)
- estimation of Carrier-to-Noise Pattern S1, S2 (2000)
- GLONASS constellation sufficient for **GLO PCV** (**2006**)
- **IGS switch from relative to absolute PCV** (igs05.atx)
  with introduction of ITRF2005 (**2006**)
- calibration of **GPS BLOCKII/IIA** satellite antenna (**2007**)
- …

Development of Absolute PCV Field Calibration

- development of robot self-calibration (2007)
- calibration of Group Delay Variations (**GDV**)/Code Variation (**2008**)
- updated set of antenna calibrations **IGS igs08.atx** (**2011**)
  adopted with new reference frame ITRF2008
- updated set of antenna calibrations **IGS igs14.atx** (**2017**)
  adopted with new reference frame ITRF2014
- …

Practical Work - Setting-Up a RTK Network:
GNSS Antenna/Near- and Far-Field Impact

Summary/Outlook

- importance of
  - verification of **GNSS station setup**
  - **GNSS antenna correction**

  has been worked out
- insight from series of GNSS antenna calibrations recommends
  - **individual antenna calibration** for precise application
- **impact of near-field multipath** can have significant impact on positioning
- proper antenna/setup has **benefits** in
  GNSS positioning **accuracy** for GNSS service **provider and user**

General Classification of GNSS Terminals

	Geodetic	Rover	Handheld
frequency bands	Multiple	single/multiple	single, L1
radiation patters	tightly optimized	controlled	uncontrolled
phase behavior	characterized and compensated in 3D	moderate, not compensated	not relied upon
multipath suppression	excellent	good	none
dimensions	large	medium	small/very small
weight	heavy	portable	almost none
cost	high	medium	very low

(from Chen, X. et al. (2012). Antennas for Global Navigation Satellite Systems. John Wiley & Sons.)

Summary/Outlook

- status GNSS antenna correction is the urgent **need for**
  - antenna PCV corrections of **new frequencies** and GNSS (eg GPS L5, Galileo E6, GLONASS L3, …)
  - azimuth dependent **satellite antenna** corrections
  - group delay variations (**GDV**)
- **requirements** to resolve issues
  - consistency
    - with existing PCV pattern
    - of PCV and GDV pattern
    - of satellite and receiver antenna pattern
  - update of ANTEX exchange format

Recommendation for … Practical Work

Thank you

for mounting
your antennas
away from
reflecting surfaces!

from: Ray, J. (2008). Systematic Errors in GPS Position Estimates.
IGS Workshop, May 11, Darmstadt, Germany.

- backup

Susceptibility of Antennas to Rain

- Dorne Margolin type GNSS chokering antenna
- **what about rainfall and use of a radome?**
- NONE
  - drop forming
  - solid water at bottom of chokerings
- SNOW radome
  - dry reception element and chokering
  - from direct rain
    - drop forming
    - water layer (or moisture) on radome

Controlled Rainfall during Absolute Antenna Calibration

- **antenna calibration**
  - under **dry weather** conditions
  - **wet weather** conditions using lawn sprinkler
- approximate rainfall intensity
  10 ... 20 mm/h during calibration
- rainfall intensity Germany

moderate rainfall	5 mm/h
heavy rain	30 mm/h
violent storm	> 50 mm/h

Sprinkling of ASH700936D_M NONE during antenna calibration

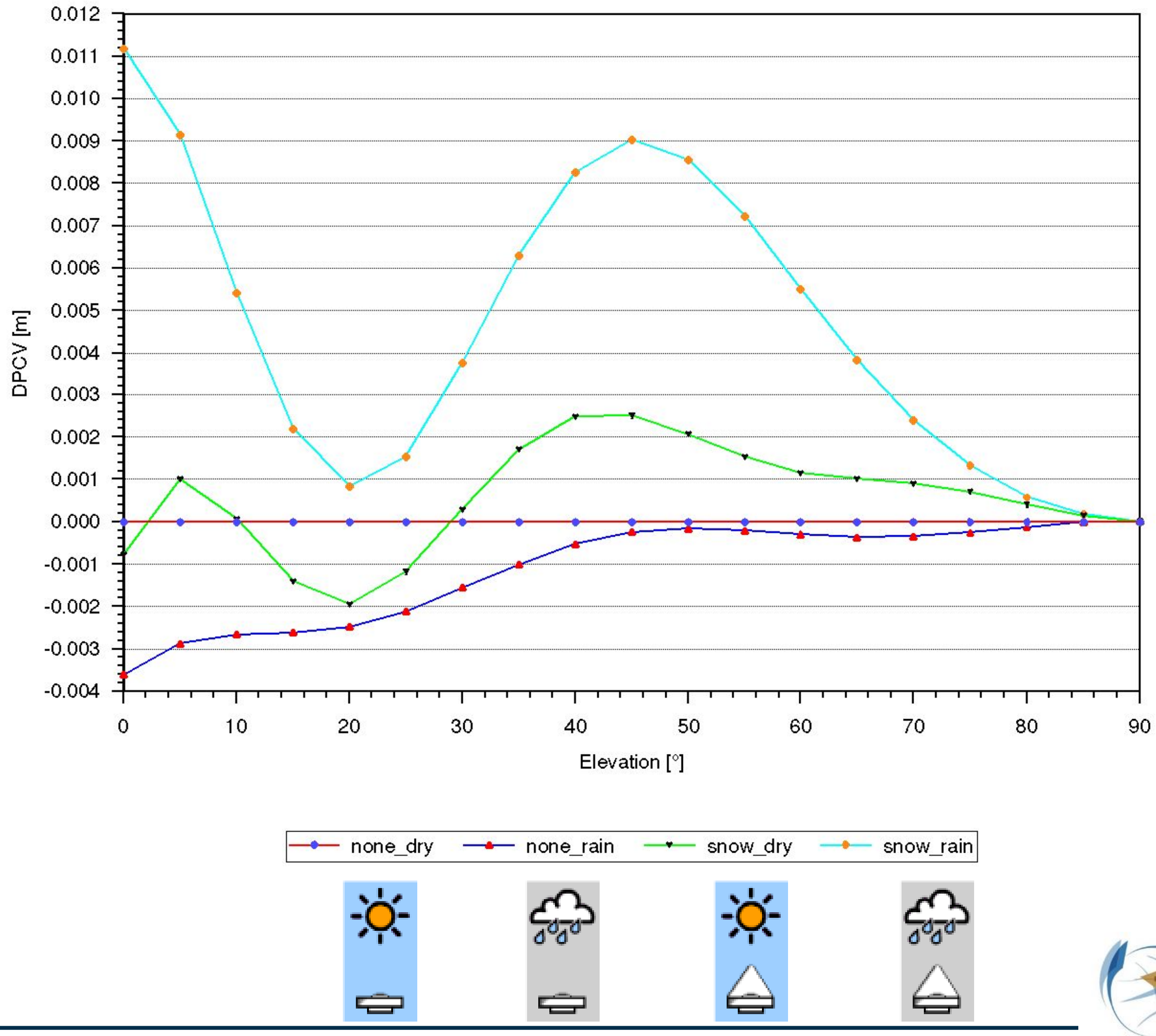
Sprinkling of ASH700936D_M SNOW during antenna calibration

Susceptibility of Antennas to Rain

- **PCV changes due to rainfall**
  for ASH700936D_M

- NONE GPS L0 < 3 mm
- SNOW GPS L0 > 10 mm

- significant compared to repeatability of individual antenna
- chokering antenna with radome more affected



L0 ionospheric free signal

Findings from Controlled Rainfall

- **PCV changes due to rainfall**
- systematic **effects in** precise **height** determination
- coordinates changes under changing weather conditions
- reception characteristics will be **superimposed by multipath**
- needs further analysis with different antenna types and different radomes

verification using static, short baseline experiment supports results of antenna calibration; 3 to 4 mm height changes due to heavy rain while using investigated antenna model ASH700936D_M SNOW.