On

GNSS Station Calibration

of

Antenna Near-Field Effects

in

RTK-Networks

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Overview

- Motivation
- Near-Field Effects / Near-Field Multipath
  - Cause and Impact
  - Robot Calibration
- Station Dependent Errors
  - Separation of Near-Field and Far-Field Effects
  - Different Treatments
- Near-Field Calibration (In-Situ) of single sites - CaNF
  - Principle, Setup, Results
- Near-Field Compensation in RTK-Networks - CoNF
- Summary/Outlook

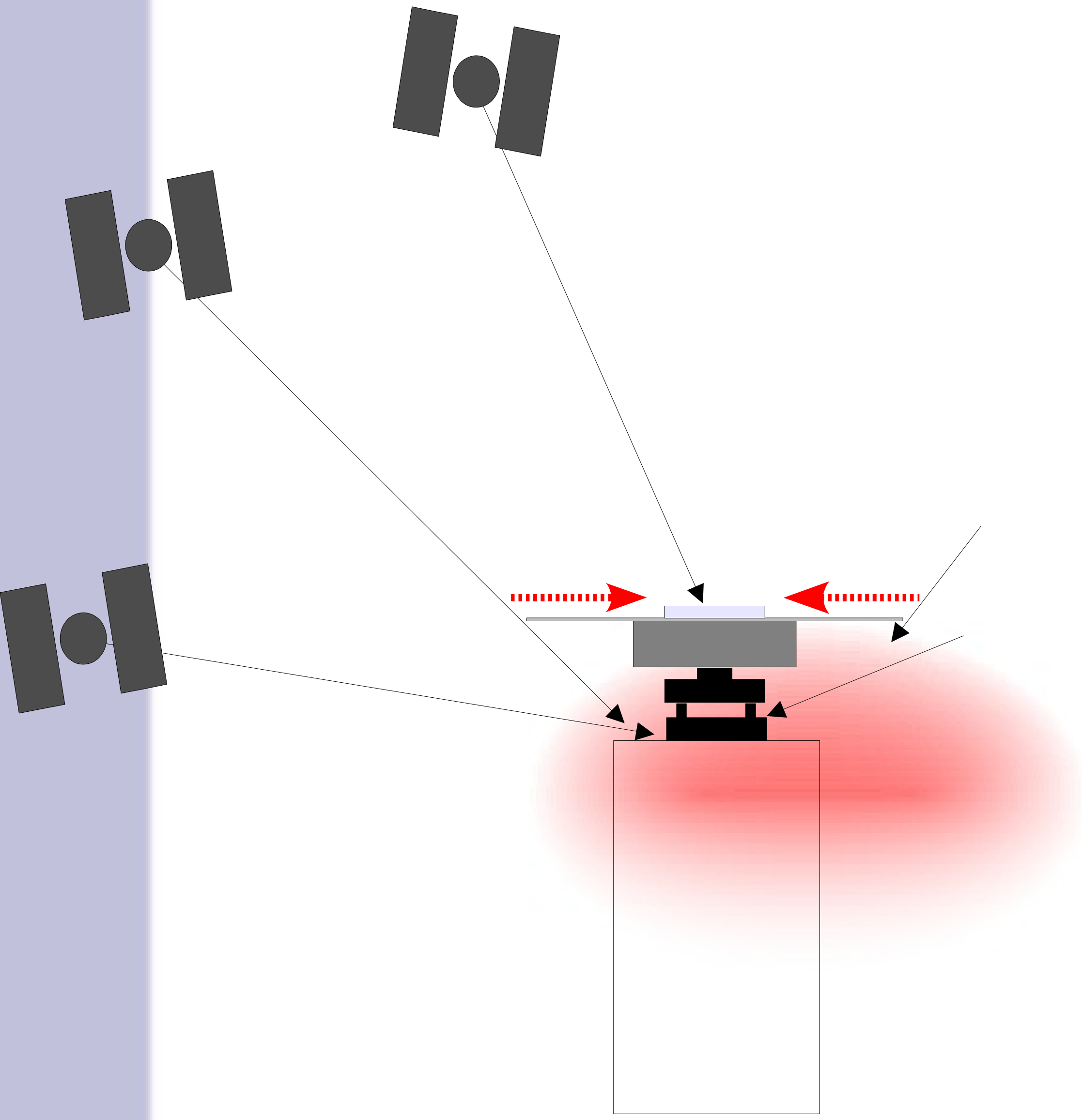
Motivation

- **Issue of near-field (NF) effects** is of increasing importance and interest in GNSS applications
- **more and more problems** due to the NF issue become obvious
  - antenna changes cause significant jumps in coordinate time series
  - non-modeled NF effects cause biased estimates for other parameters in a GNSS application
    - tropospheric zenith delay, tropospheric gradients,
    - coordinates
    - carrier phase ambiguities
    - …
  - and therefore reduce the performance (accuracy, availability, reliability) of the GNSS applications

Motivation

- Strategies/methods for **determination/correction/handling of NF** effects are required to
- **improve the accuracy, availability and reliability of GNSS applications**
  - permanent reference stations, coordinate time series
  - RTK networks – service performance and integrity
  - precise height determination using GNSS methods
  - kinematic platforms (strong NF effects of car roofs, in-situ calibration)
  - ...

Near-Field Effects: Cause

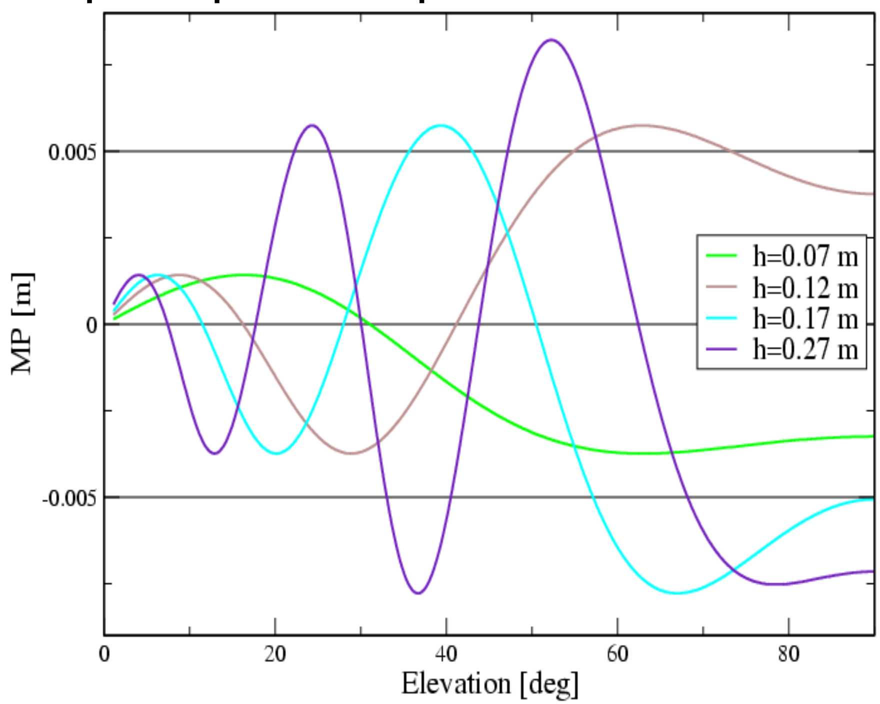


- antenna near-field depends on
  - antenna type
    (plus radome construction, ...)
  - mount/setup
    (tripod, tribrach, adaption, ...)
  - station environment
    (pillar, roof, ...)
  - weather conditions
    (reflecting coefficient, snow, ...)
- effect on signals due to
  - reflection
  - diffraction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

Near-Field Multipath: Theoretical Impact

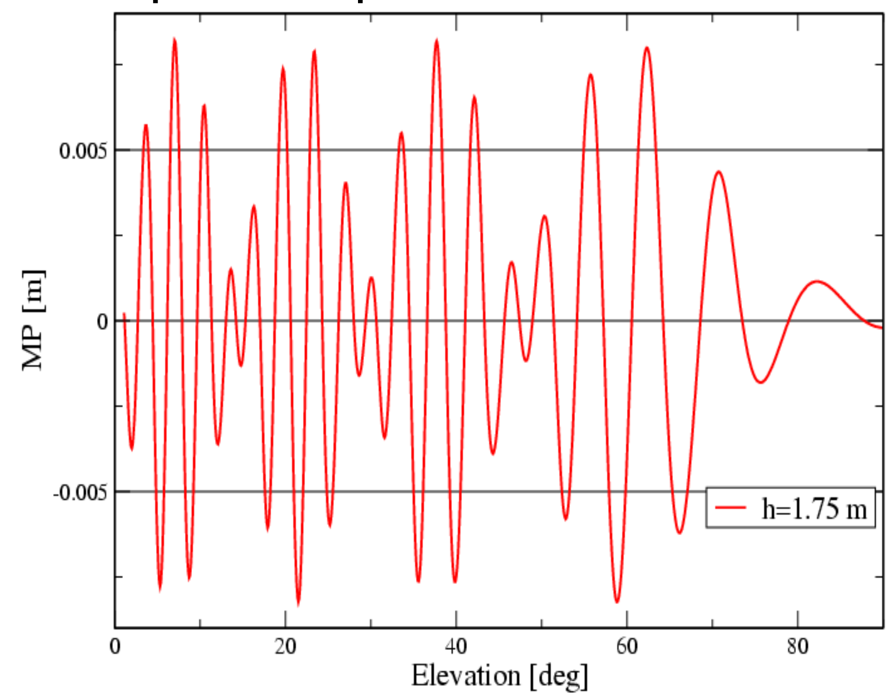
model assumption: horizontal reflector

- pillar/pier setup



- high “spatial” wavelength
- effect in all elevation areas
- non-zero average
- systematic coordinate errors

- tripod setup



- low “spatial” wavelength
- effect in all elevation areas
- zero average over short observation times

IGS Warning/Recommendation (Jim Ray, NGS, 2008)

BRFT

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.

Station Dependent Errors

- Geo++ philosophy: separation 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 and model highly variable total MP in an operational procedure**
- Strategy: separation of near-field (NF) and far-field (FF) multipath

  $dS = PCV + \mathbf{MP}_{NF} + \mathbf{MP}_{FF}$
- Methods to determine and mitigate NF effects

  In-Situ Station Calibration

Near-Field Multipath: Robot Calibration

- determination with precise robot calibration
  - standard deviation 0.2 bis 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

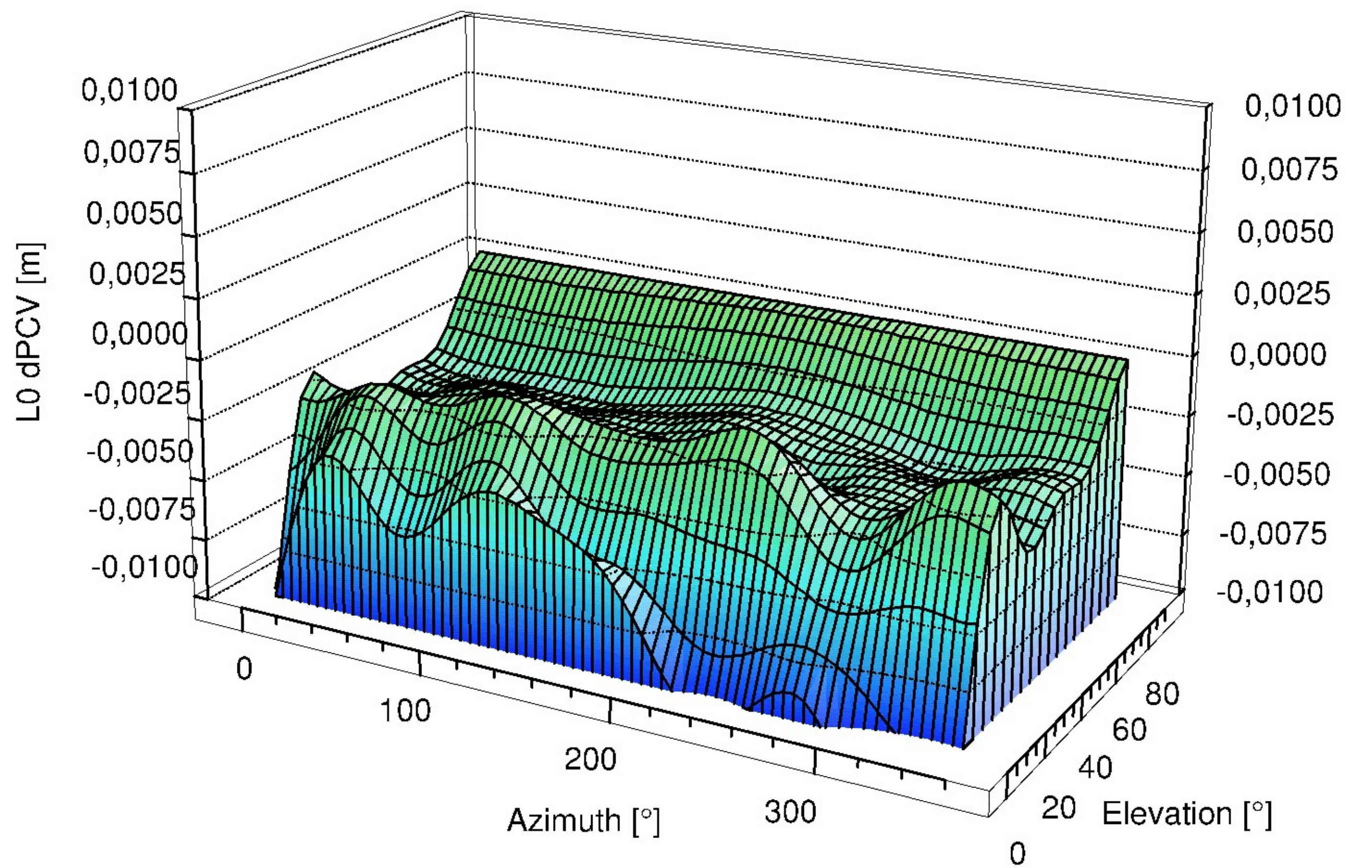
PCV phase center offsets and variations
MP multipath

Near-Field Multipath: eg Impact on DM-Type Chokering Antenna

- ASH700936D_M
- reconstruction head of pillar/tribrach
- ∅ 19cm/Δ Zeiss
- difference L0 PCV against regular calibration
  - 10-30° elevation

    mean ca. 2 mm
    maximum 7 mm
  - 40-70° elevation

    mean ca. 2 mm
    maximum 3 mm
  - impact in range domain!



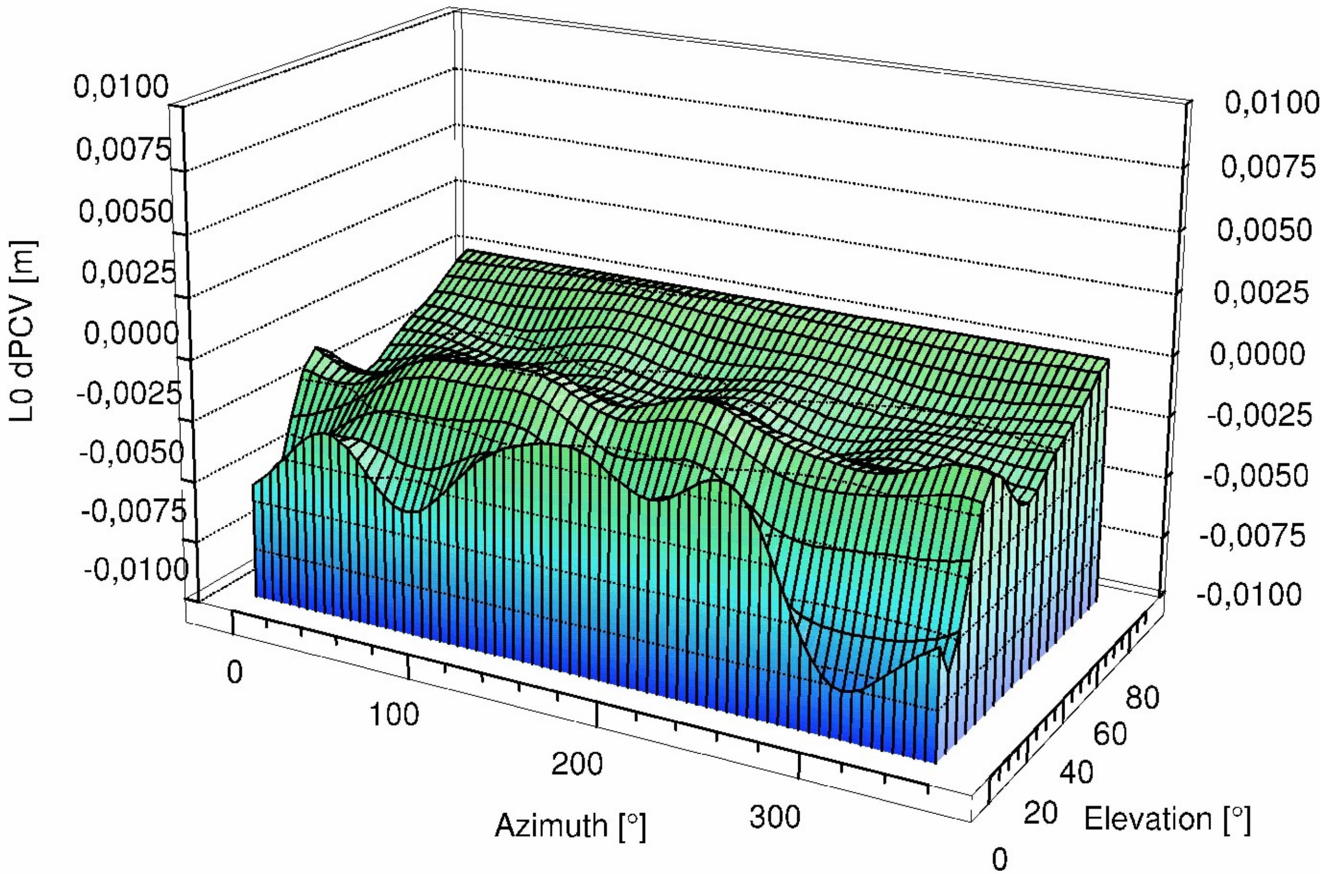
L0 ionospheric free linear combination

Near-Field Multipath: eg Impact on DM-Type Chokering Antenna

- ASH700936D_M
- reconstruction head of pillar/tribrach
- 30x30 cm/Δ Zeiss
- difference L0 PCV against regular calibration
  - 10-30° elevation

    mean ca. 2 mm
    maximum 6 mm
  - 40-70° elevation

    mean ca. 4 mm
    maximum 5 mm
  - impact in range domain!

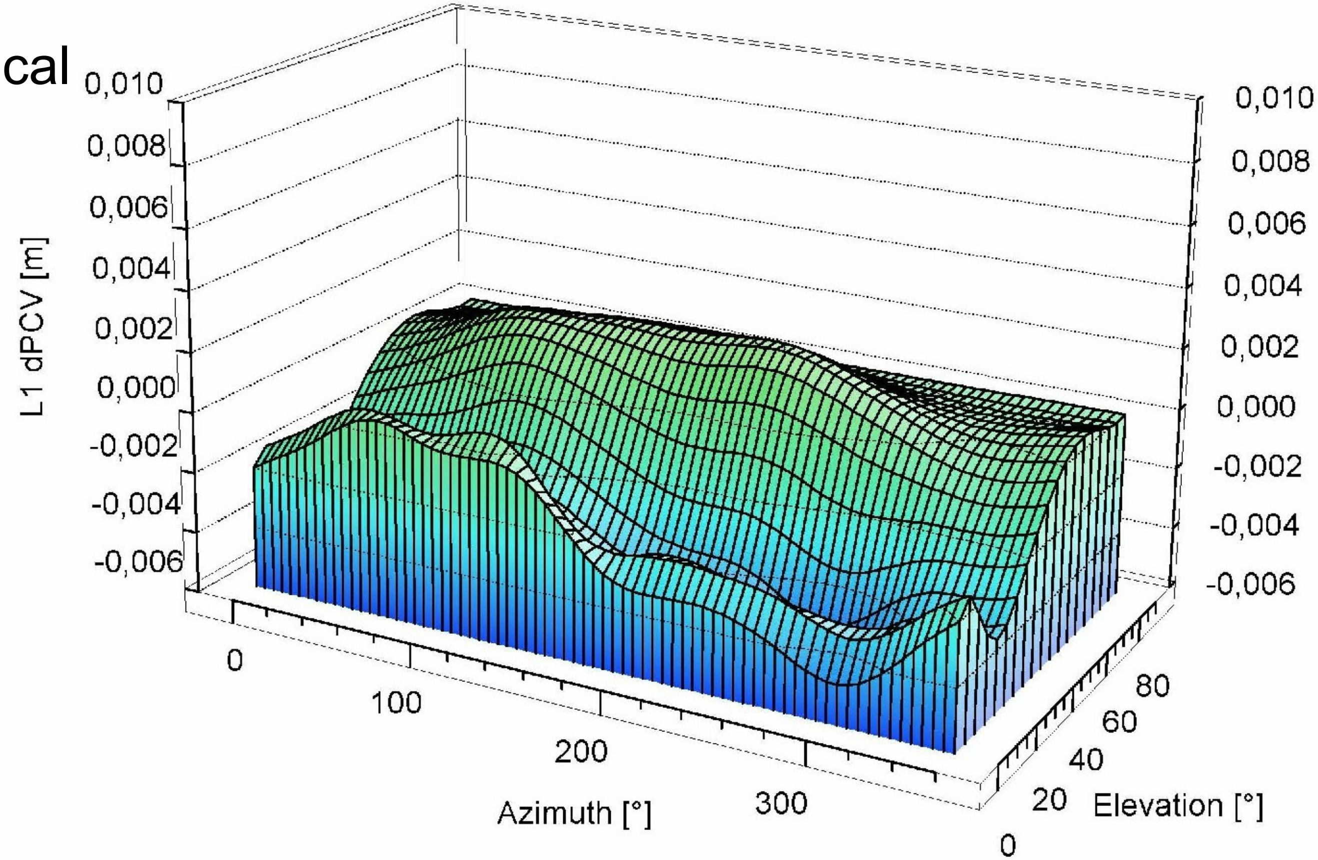


Real Life Example from RTK Networking

- TPSPG_A1 GNSS antenna
- 10 cm prism spacer and special construction with two ground planes ca. ∅ 14 cm
- 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

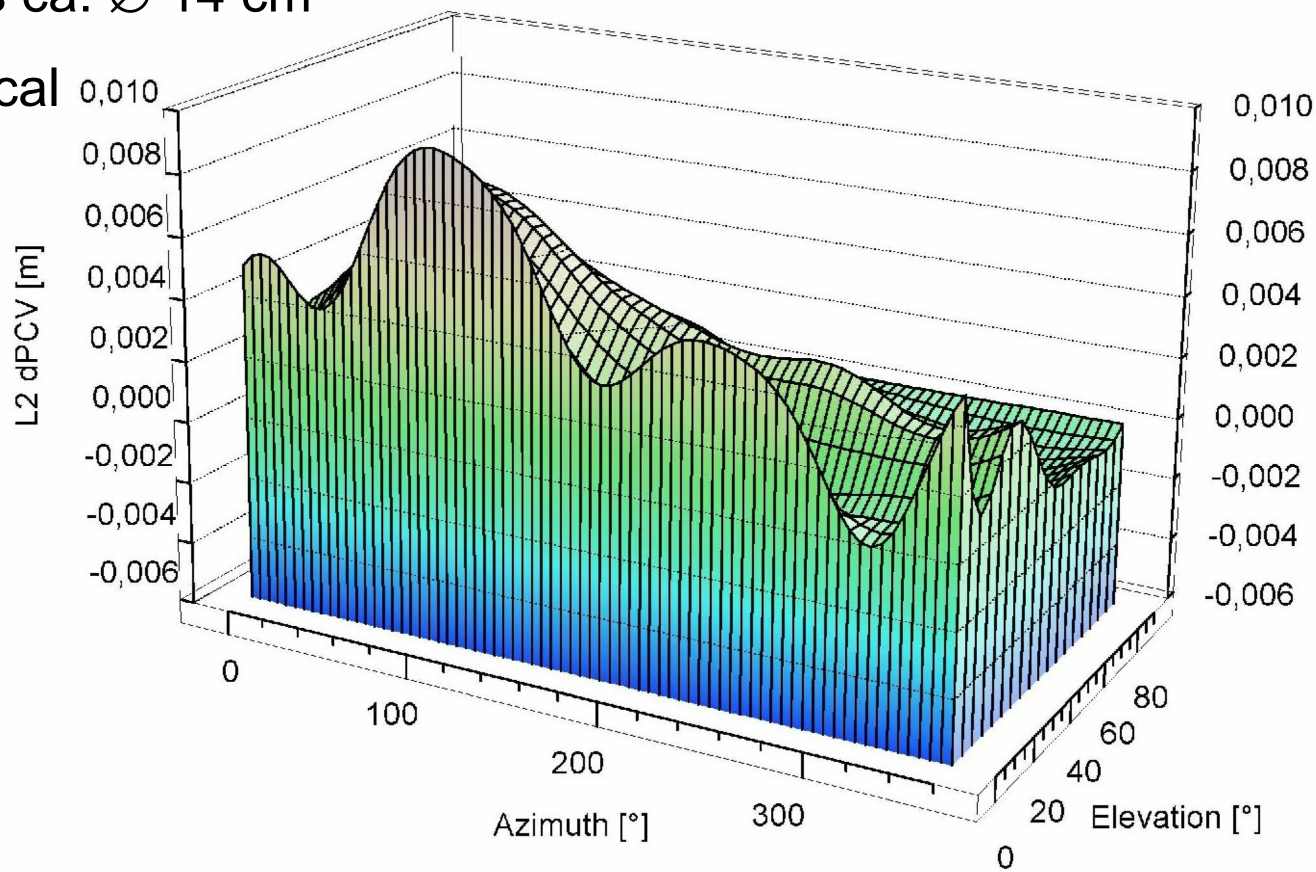


Real Life Example from RTK Networking

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

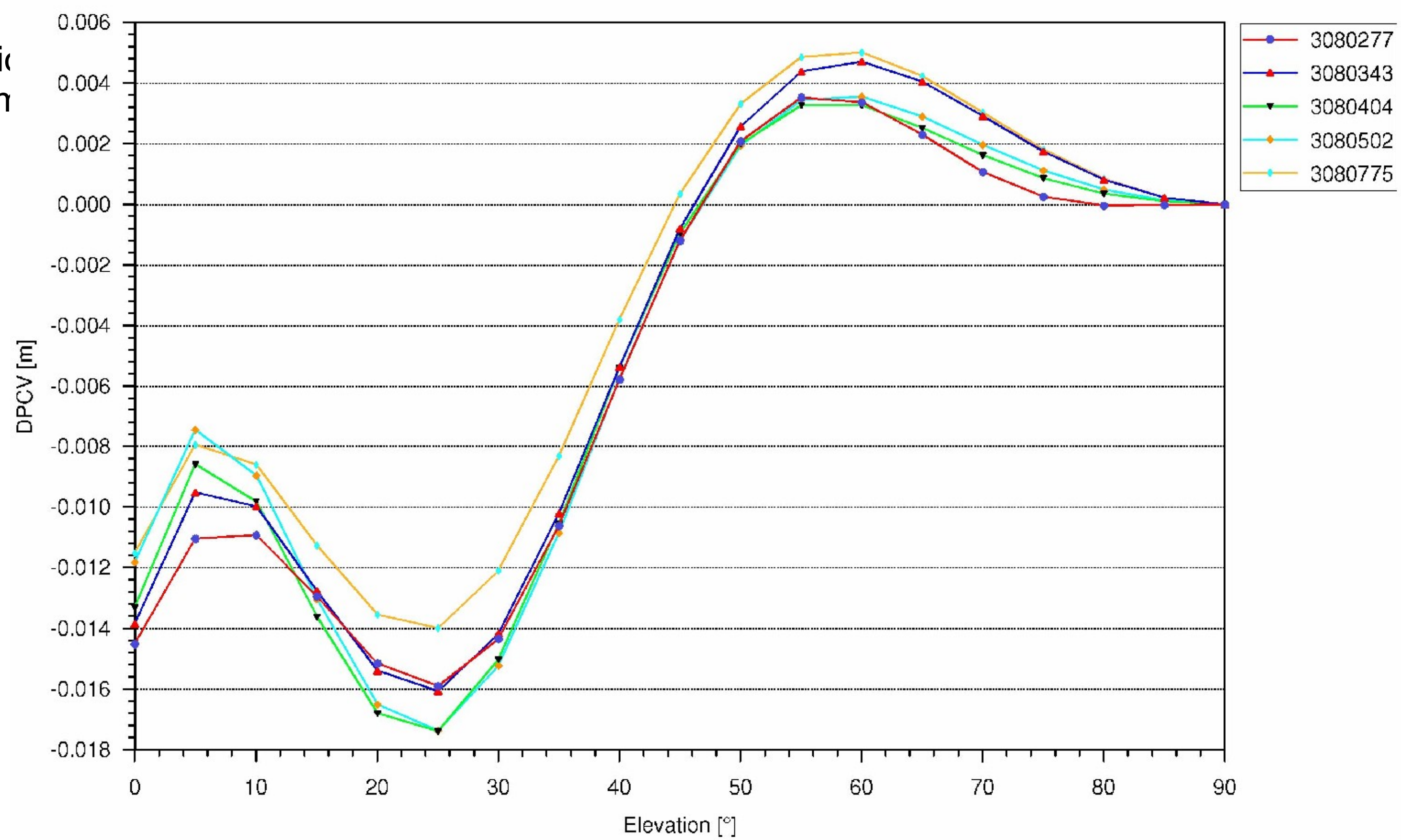
    mean ca. 4 mm
    maximum 8 mm
  - 40-70° Elevation

    mean ca. 1 mm
    maximum 4 mm

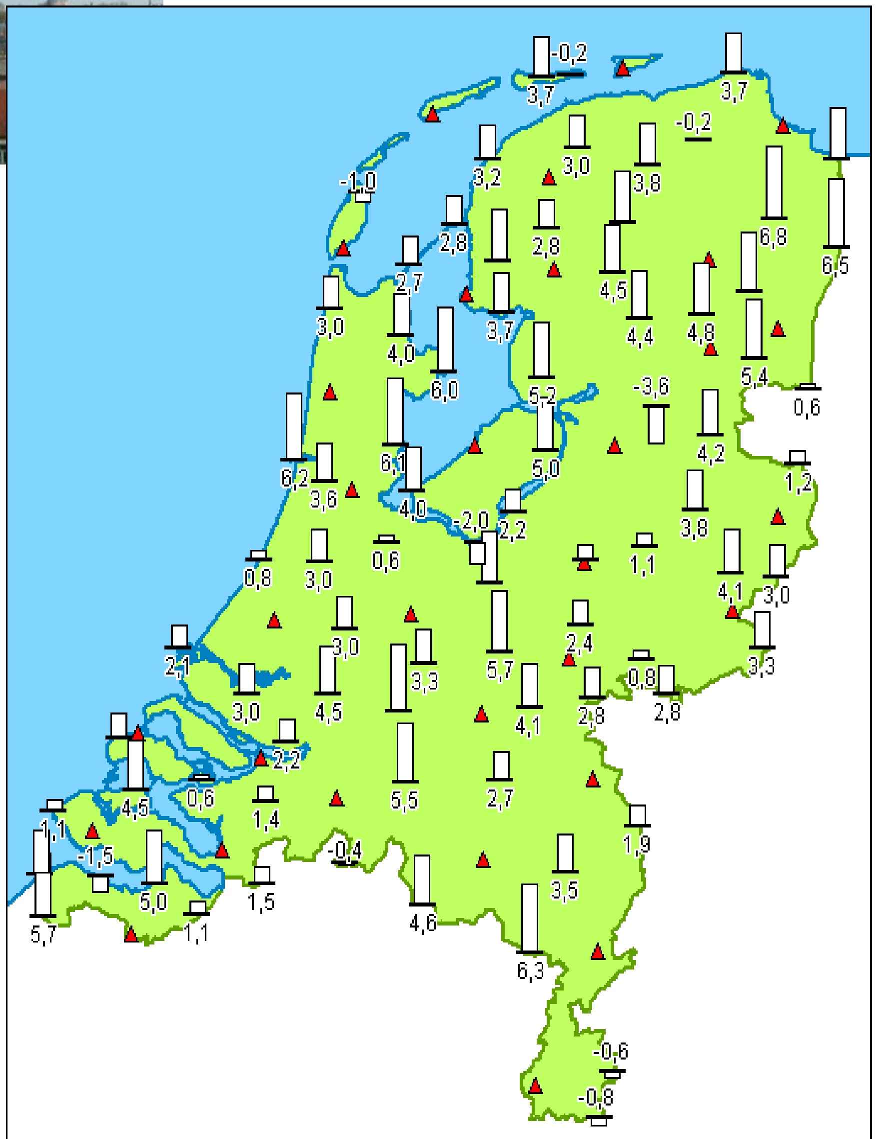


Real Life Example from RTK Networking

- amplification for L0 PCV
- L0 PCV differences against
  - 10-30° elevati maximum -18 mn
  - 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
- 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 errors mean height difference is -2 mm (49 points)

results and graphic have been kindly provided by Kadaster, The Netherlands

Station Dependent Errors: Different Treatments

	Error	*Characteristic*	*Treatment*
Antenna	PCV	elevation and azimuth dependent PCV	calibration of PCV using robot
Multipath	$MP_{near\text{-}field}$	long-periodic, systematic effect, bias	calibration of near-field effects using robot/ in-situ station calibration
	$MP_{far\text{-}field}$	short-periodic, systematic effect	averaging over time, absolute s tation calibration or weighting (CN0) sidereal differences (GPS only)
Station Uncertainty		stable unterground, setup, monumentation	analysis of time series

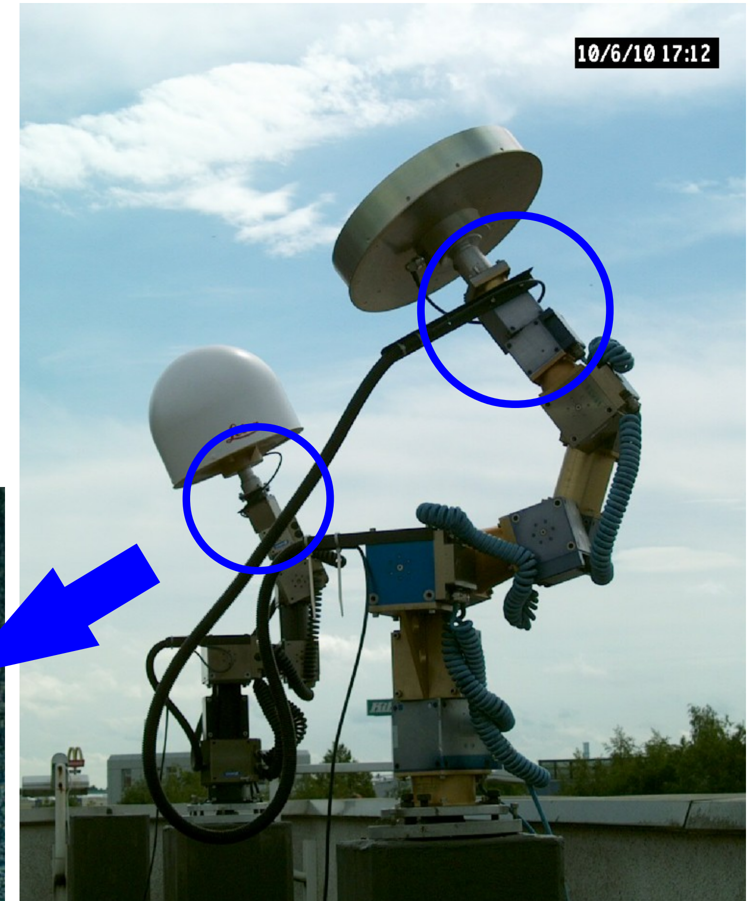
CN0 carrier-to-noise

Determining NF effects of a Reference Station

	Approach	***Method***
1	explicit determination	robot calibration (since 2002)
2	noisifying multipath	station calibration using robot (Böder et al. 2001)
3	averaging multipath	multiple station setup (Wübbena et al. 2006)
4	determine near-field correction and weighting from L1 & L2 residuals	in situ station calibration with calibrated, multipath free equipment (method 1) - CaNF
5	determine near-field correction and weighting from L0 residuals in redundant setups	in situ station calibration/ NF compensation within a network of GNSS reference stations - CoNF
6	combination of approaches	use of some in situ calibrated stations (method 4) and apply it to constrain method 5 - CNF

In-Situ Site Calibration (CaNF): Near-Field Free Station

- individual absolute GNSS antenna calibration
- optimal control of near-field effect required
  - mock-up of top robot and mount
  - best approximation of all errors (near-field and PCV of antenna)



○ top of robot with mount

In-Situ Site-Calibration (CaNF): Near-Field Free Station

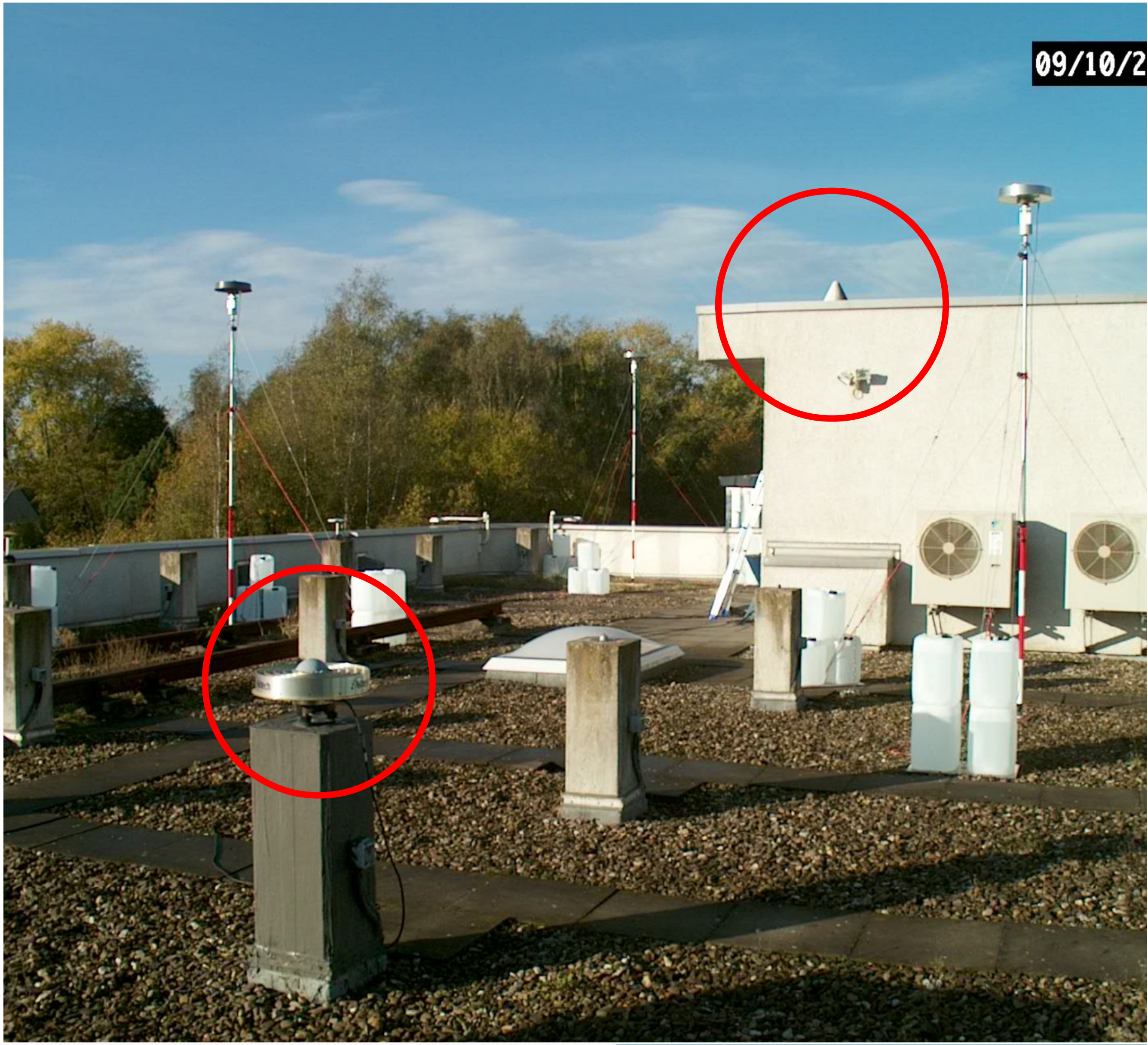
- mock-up of antenna's robot calibration
  - no near-field multipath
- high and slight setup on a pole (~ 3 m)
  - reducing far-field multipath
- short distances
  - no impact from atmospheric or orbit errors
- setup and system design
  - transportable
  - flexible
  - scalable
  - easy to use
  - ...

In-Situ Site Calibration (CaNF): Setup

- ○ near-field free temporary stations
- redundant setup with three stations (or more)
- stations must cover GNSS visibility of reference stations
- sophisticated GNSS receivers with coupled clocks

In-Situ Site Calibration (CaNF): Setup

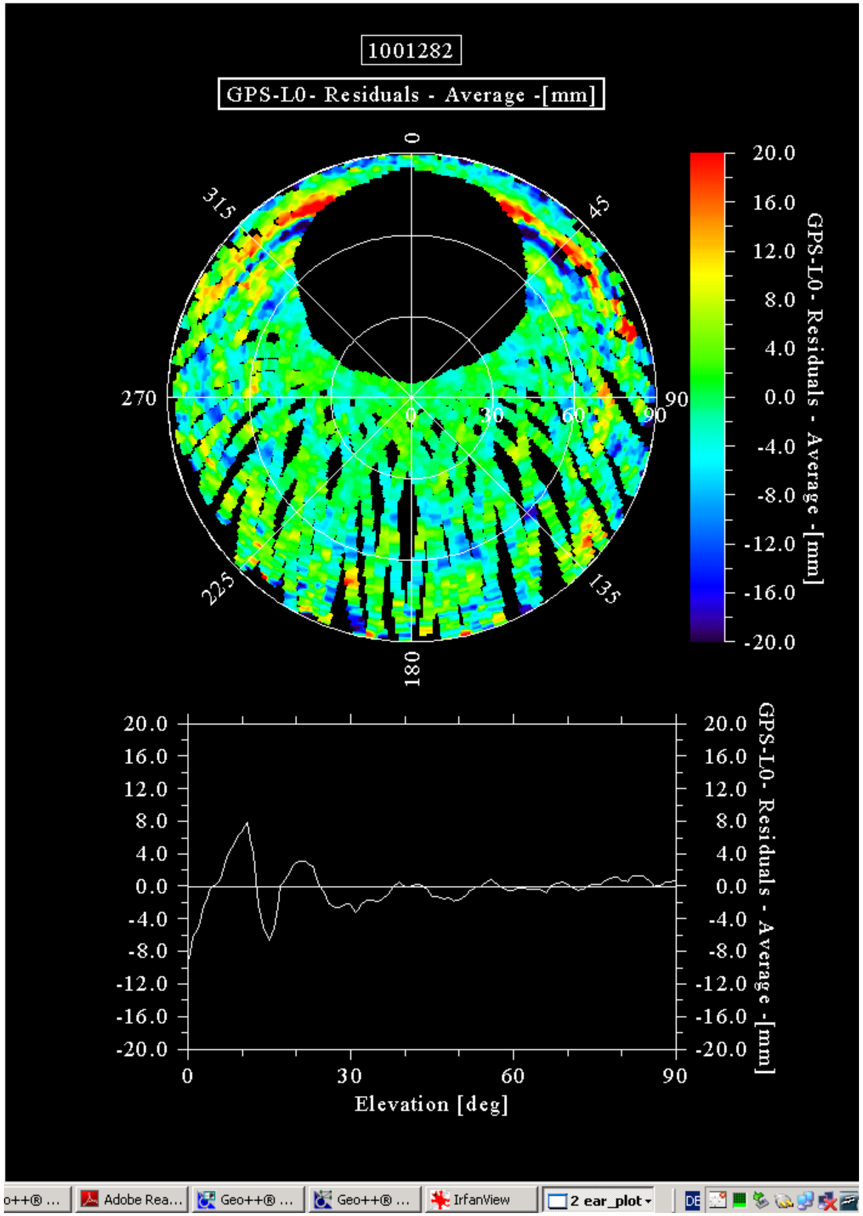
- O reference stations to be calibrated
- original receiver substituted through in-situ calibration system receiver using antenna splitter
- coupled clock with NF-free stations
- 1 Hz data rate
- 0° cut-off
- at least 24 h data
- 9 days for complete GLONASS calibration



In-Situ Site Calibration (CaNF): Reference Stations

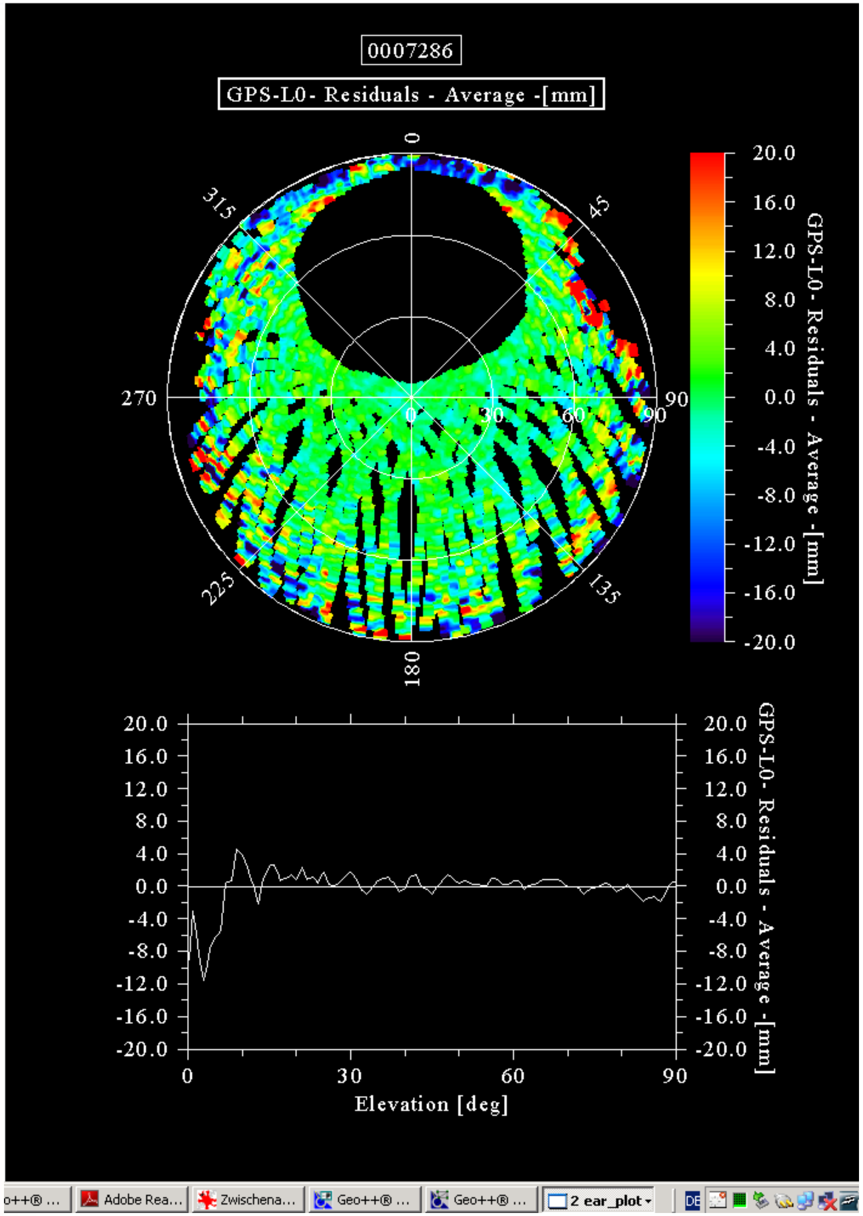
- experiment on Geo++ roof
- reference station on roof top (1000/1001)
  - close objects
  - flat reflectors
  - remote reflectors
- reference station on pillar (0007)
  - standard setup
  - pillar top is reflector
  - remote reflectors

In-Situ Site Calibration: Residual Analysis



- 24h doy 282-283, 2009 reference station (roof top, 1000/1001)
- GPS L0 residuals shown
- basically no obstructions
- prominent band in N (280°-80°) up to ~10°-15° elevation
- up to 4 cm residual changes over small elevation range

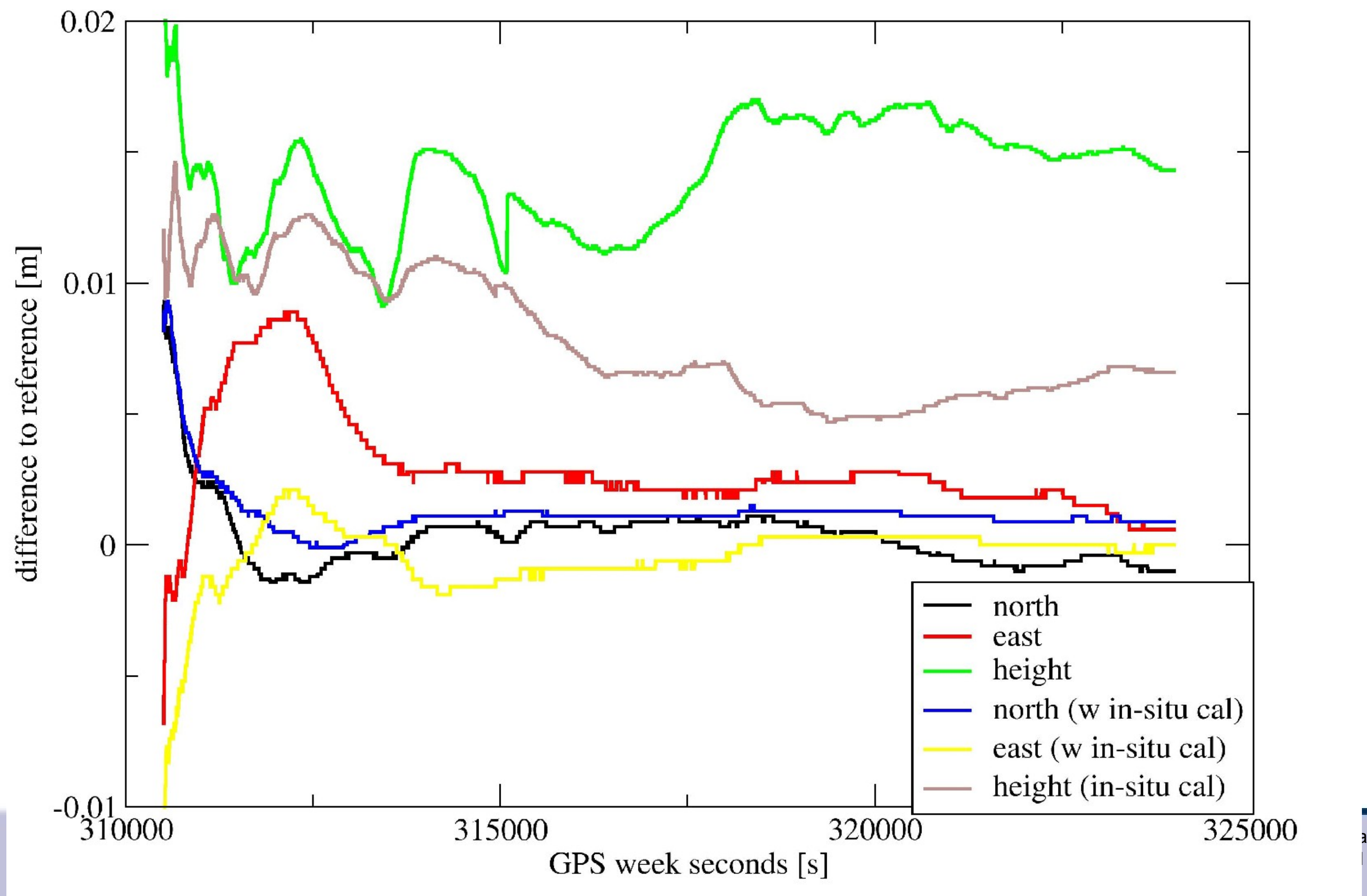
In-Situ Site Calibration: Residual Analysis



- 24h doy 286-287, 2009 reference station (pillar, 0007)
- GPS L0 residuals shown
- obstructions in W (building) and NE (45°-90°, tree)
- alternating pattern reaching 30° elevation over complete azimuth range
- up to 2 ... 4 cm over small elevation range

In-Situ Calibration: Applying Correction/Weighting

- static GPS **L0 processing with troposphere estimation**
- **standard** approach and **with in-situ correction/weighting** applied
- difference to reference coordinates (horizontal GNSS, leveled height*)



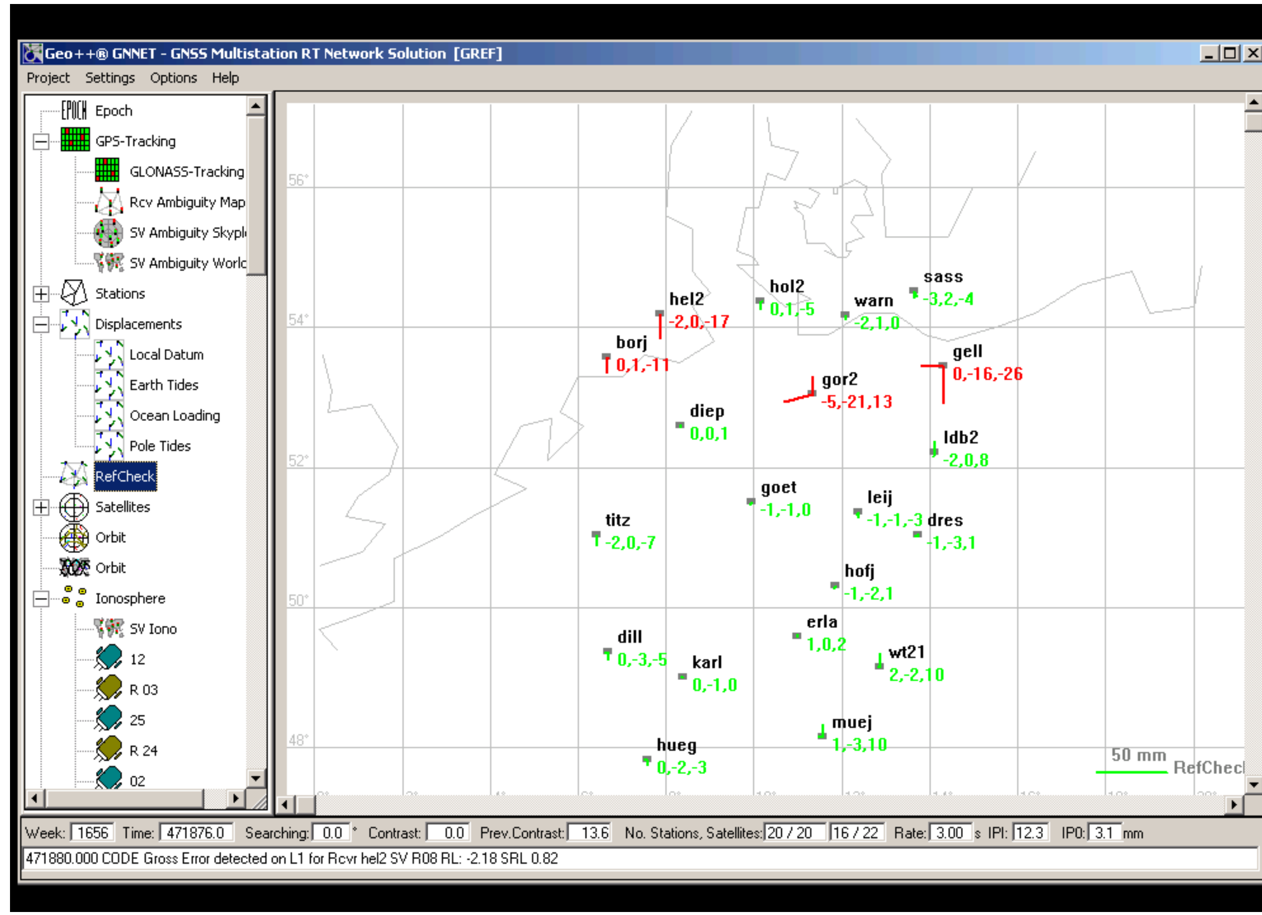
* to be checked!

CoNF – Compensation of Near-Field

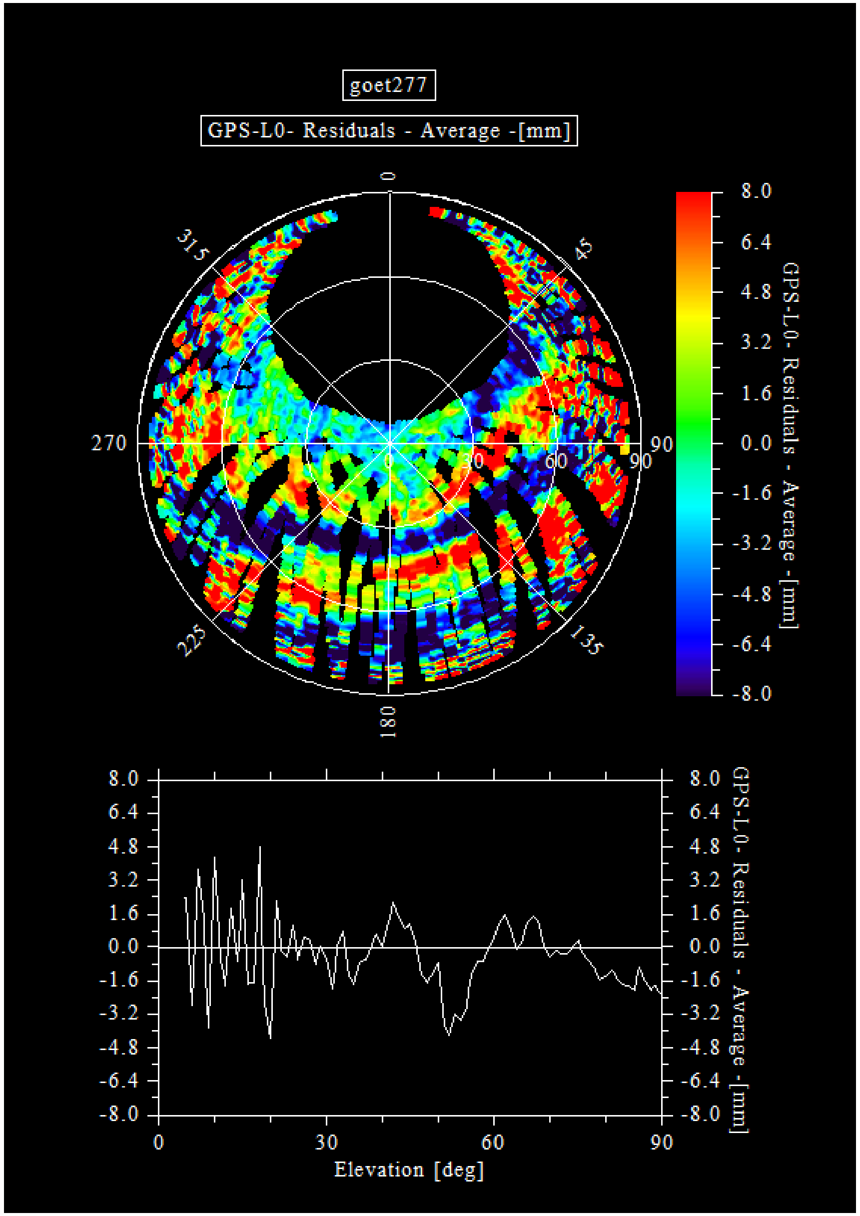
- Compensation of Near-Field for all network stations
  - utilizes redundancy in GNSS networks
  - determines the near-field effect of all reference stations in a network
  - derives corrections and weighting schemes from non-differenced ionospheric free signal L0 residuals
  - L1/L2/L5 not fully accessible due to non-distinguishable ionospheric effects
  - elevation-azimuth dependent model

CoNF: Network

- GREF network
- 20 reference stations
- automatic procedure to estimate correction and weighting
- automatic application of correction and weighting

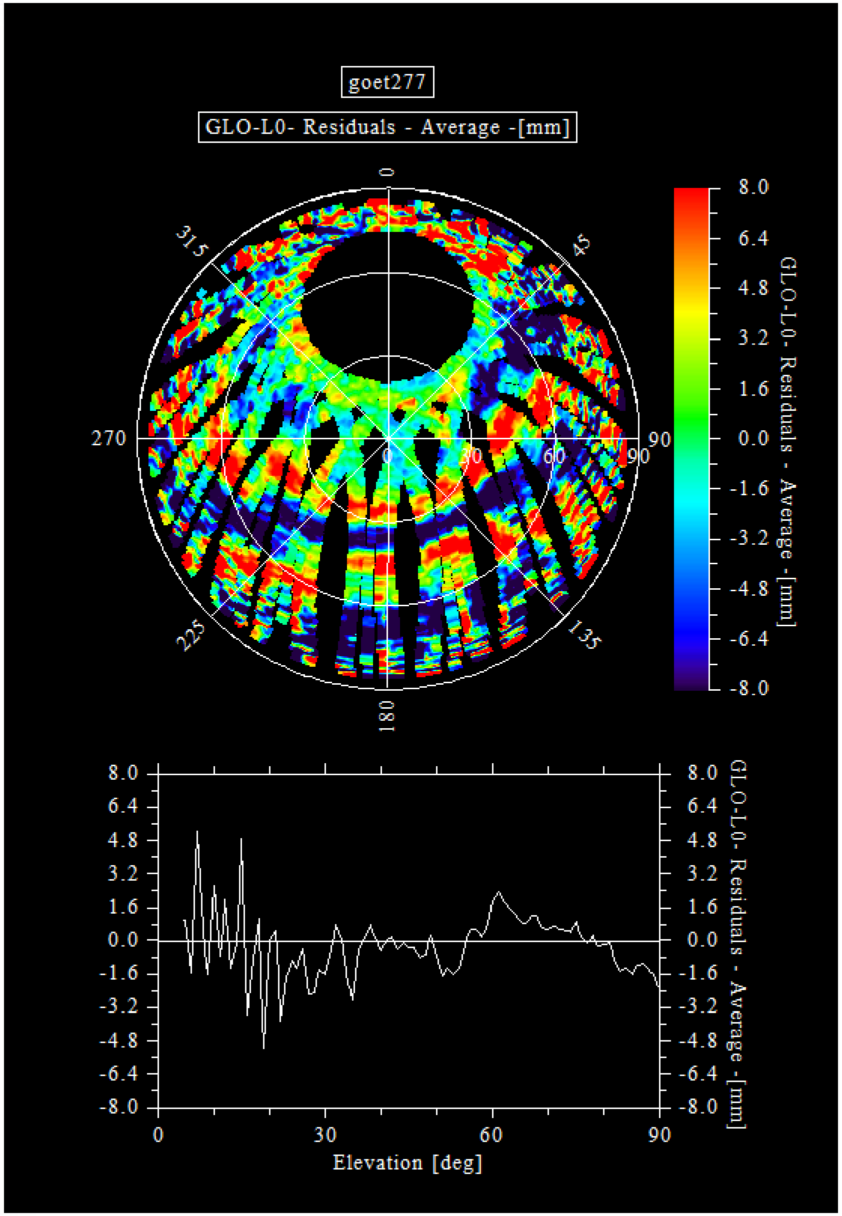


CoNF: Residual Analysis



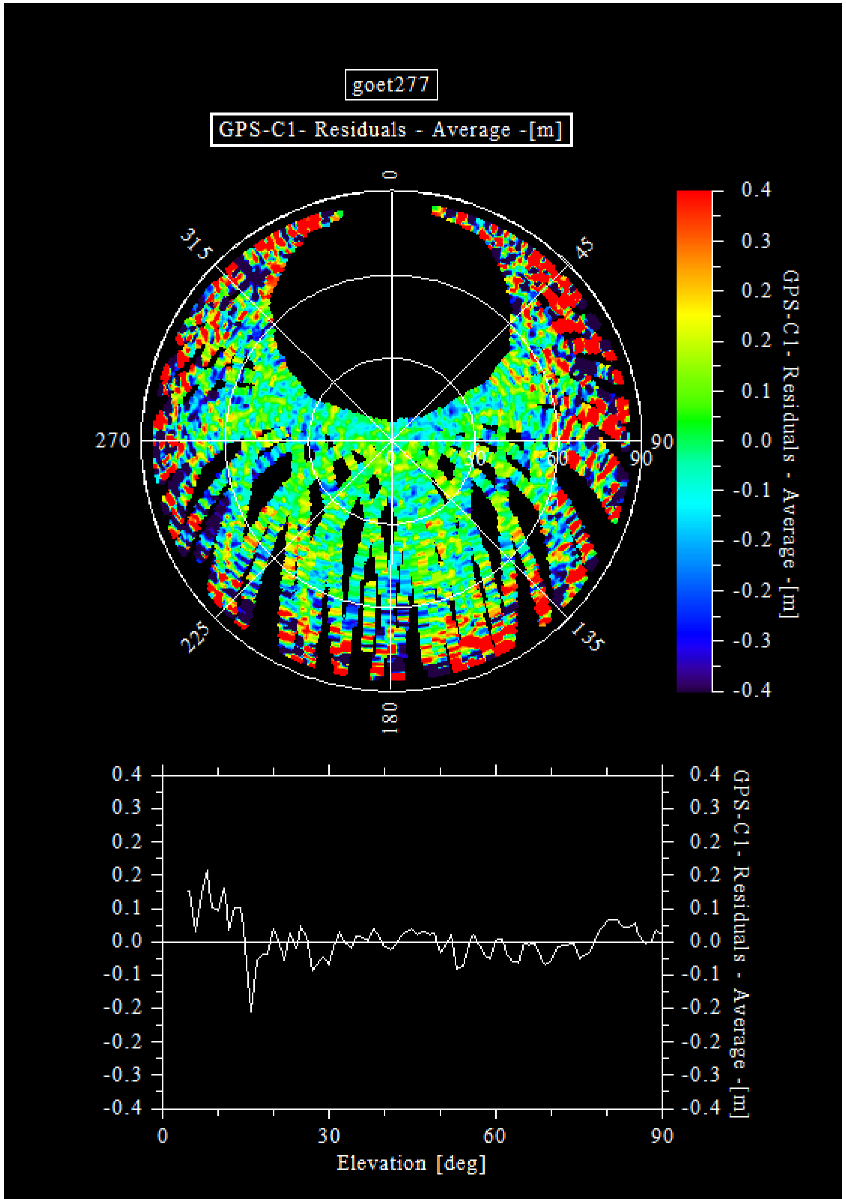
- iterative estimation from GREF network
- several days, 2011 reference station GOET
- GPS L0 residuals shown
- basically no obstructions
- prominent band in EW up to ~30°-60° elevation
- significant systematic residual changes

CoNF: Residual Analysis



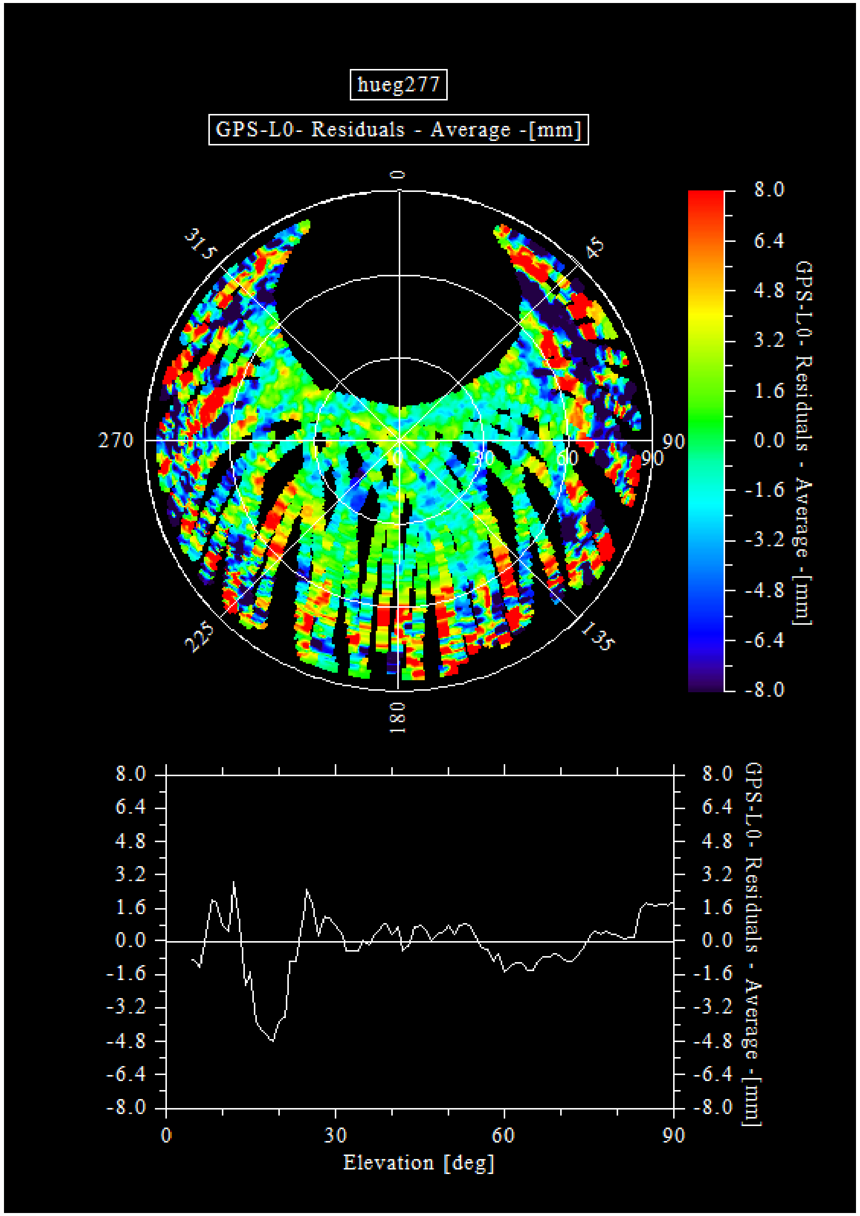
- iterative estimation from GREF network
- several days, 2011
  reference station GOET
- GLO L0 residuals shown (frequency independent)
- basically no obstructions
- prominent band in EW
  up to ~30°-60° elevation
- significant systematic residual changes

CoNF: Residual Analysis



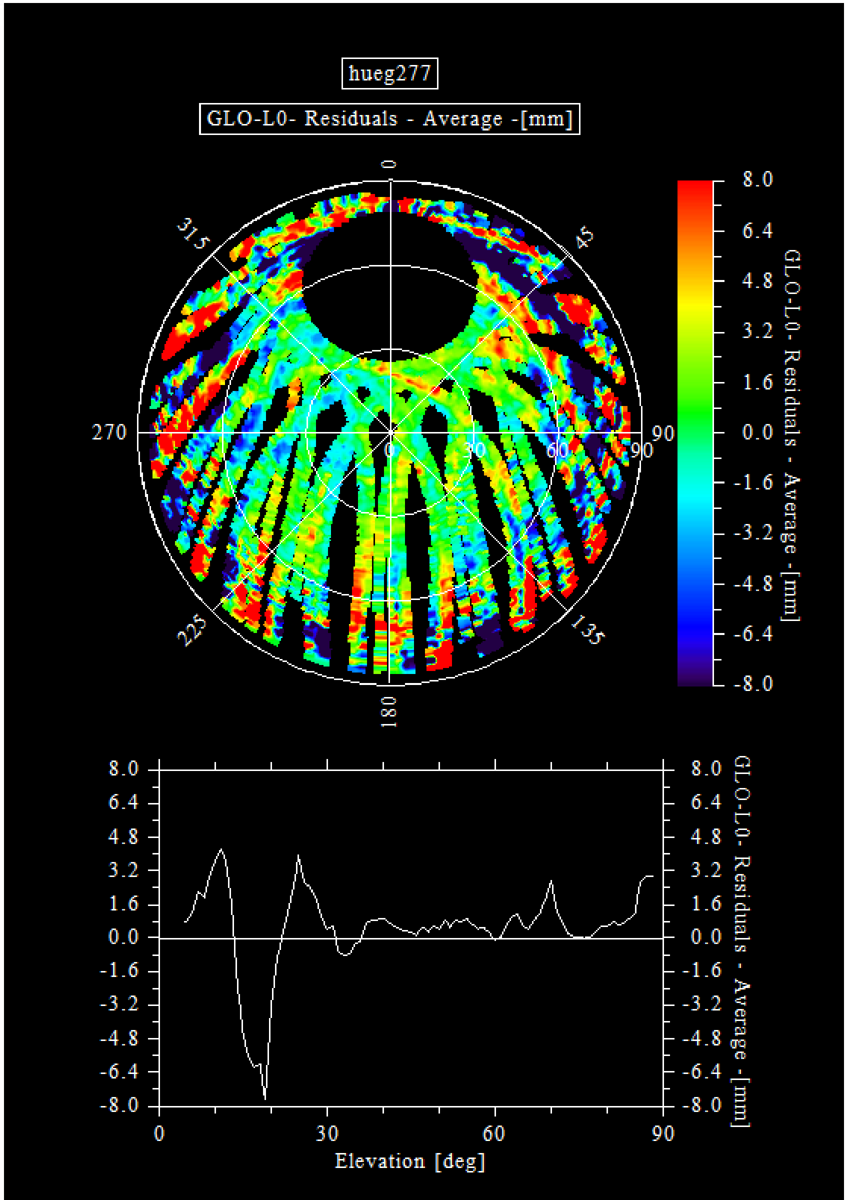
- iterative estimation from GREF network
- several days, 2011 reference station GOET
- GPS C1 residuals shown
- basically no obstructions

CoNF: Residual Analysis



- iterative estimation from GREF network
- several days, 2011 reference station HUEG
- GPS L0 residuals shown
- basically no obstructions
- roof visible in plot

CoNF: Residual Analysis



- iterative estimation from GREF network
- several days, 2011 reference station HUEG
- GLO L0 residuals shown (frequency independent)
- basically no obstructions
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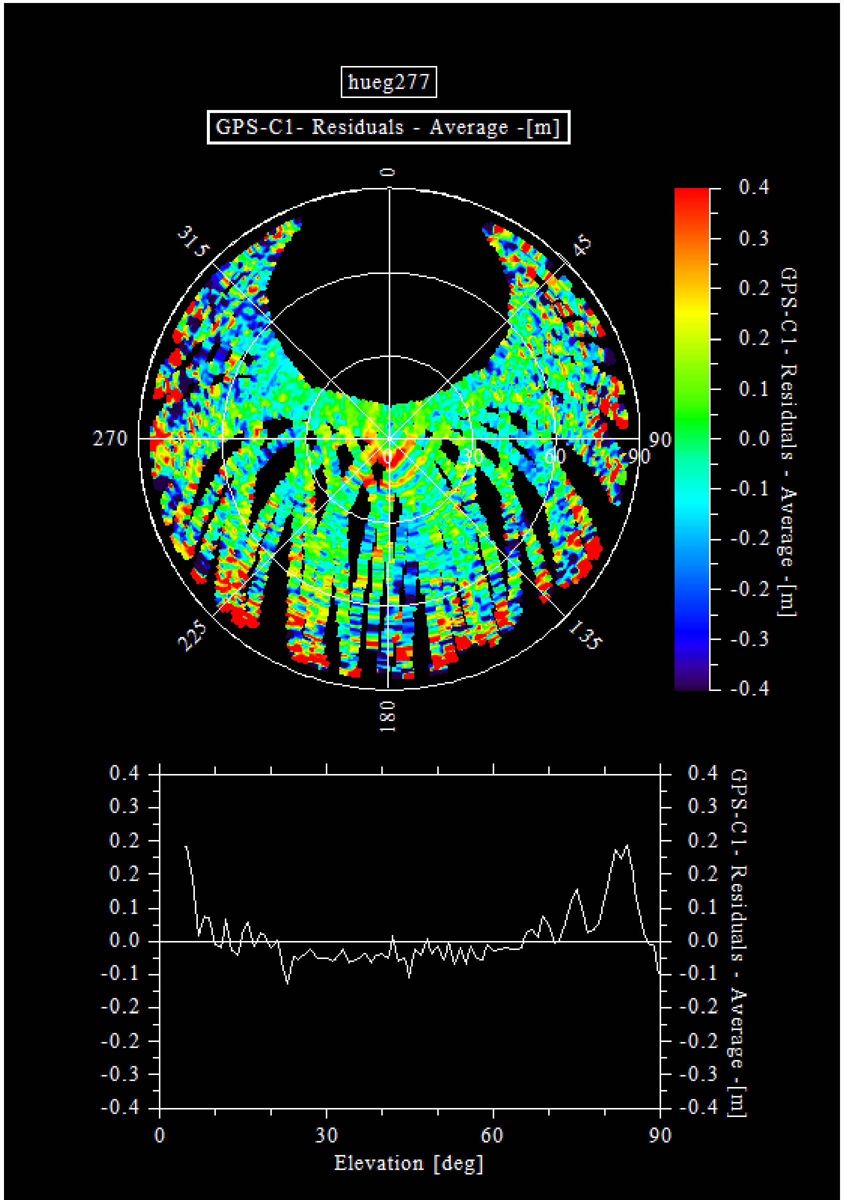
CoNF: Residual Analysis



- iterative estimation from GREF network
- several days, 2011 reference station HUEG
- GPS C1 residuals shown
- basically no obstructions

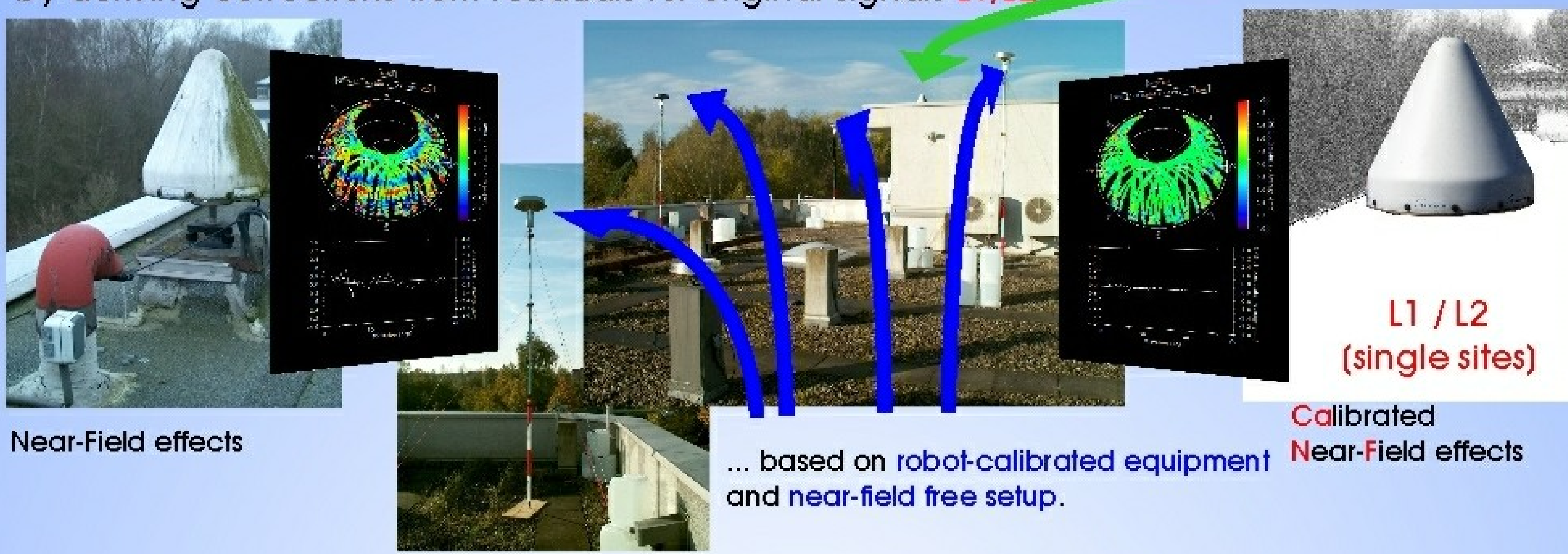
CNF – Calibration + Compensation of Near-Field

- Determination of NF corrections and weighting for all network stations and original signals
  - CaNF calibrations for some selected sites in a network
  - constraining CoNF with results from CaNF
  - separation of original signals (L1/L2/L5) instead of ionospheric free signal L0 becomes possible through appropriate ionospheric modelling
  - L1/L2/L5 corrections and weighing schemes for all network sites

Summary CaNF

CaNF (Calibration of Near-Field) of one single site

Determines the near-field and to some degree also the far-field multipath of one single site by deriving corrections from residuals for original signals L1/L2



Near-Field effects

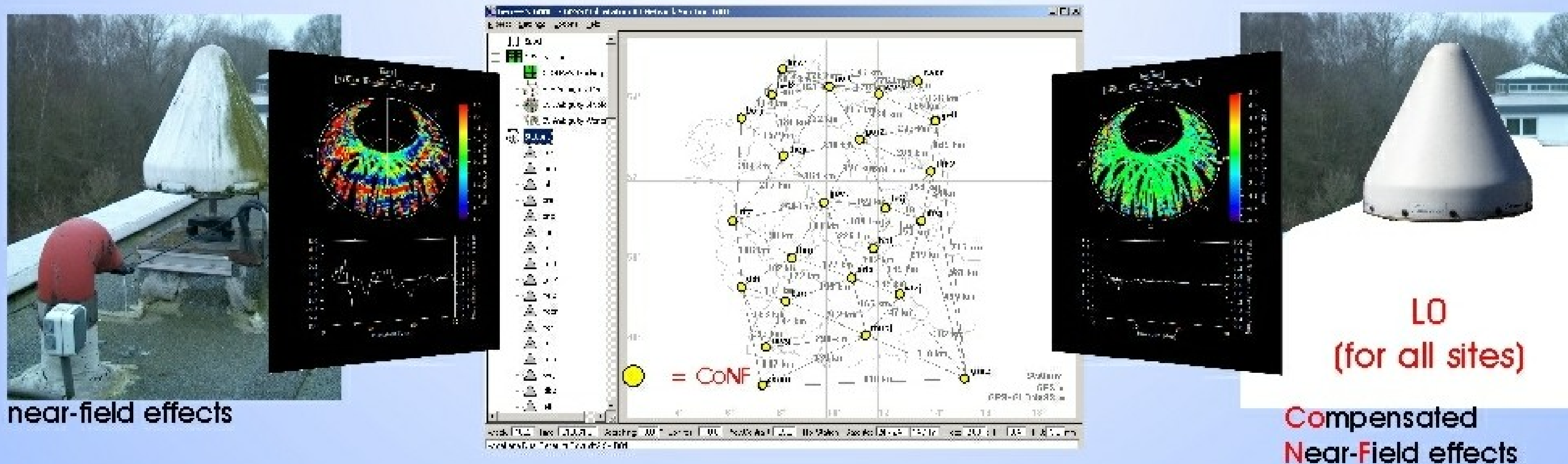
... based on robot-calibrated equipment and near-field free setup.

Calibrated Near-Field effects

Summary CoNF

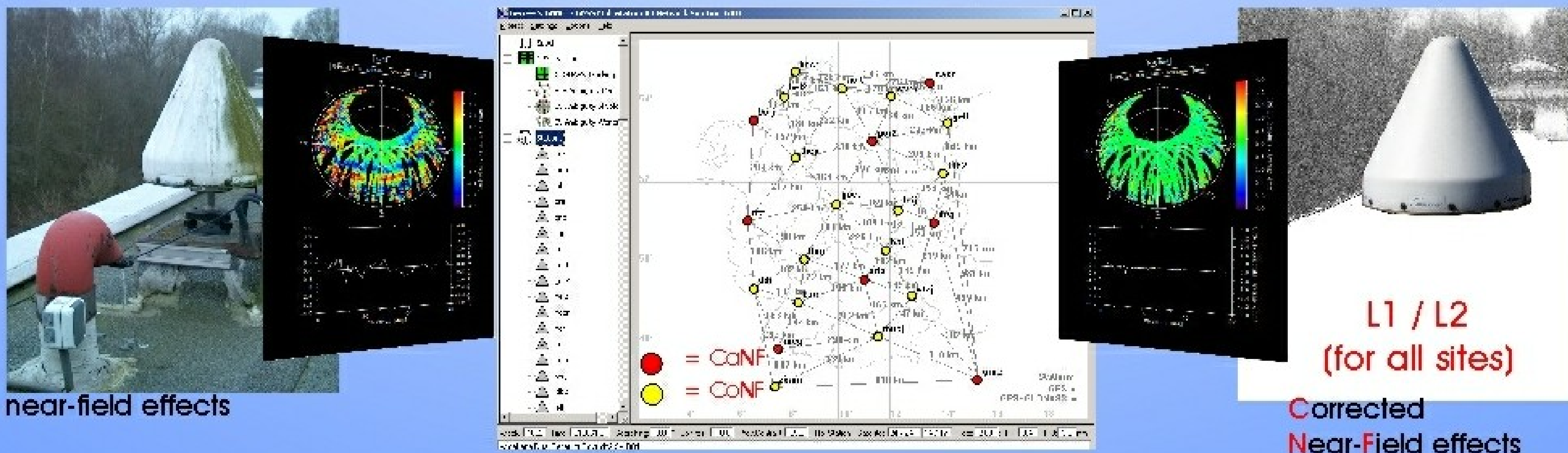
CoNF (Compensation of Near-Field) for all network stations

Determines the near-field for all reference stations in a network
by deriving corrections from residuals for ionospheric free signal L0.



Summary CNF

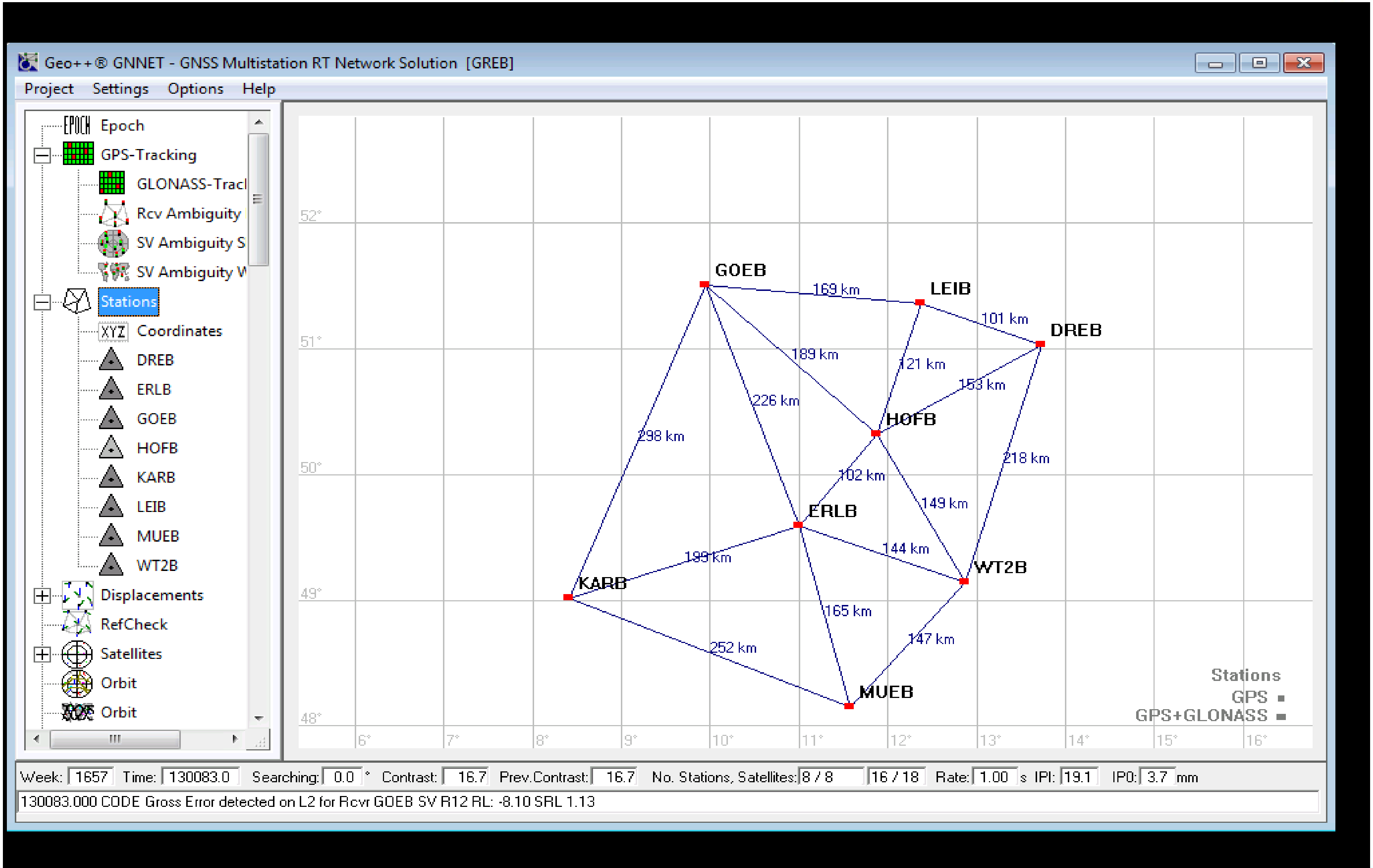
CNF = CaNF+CoNF (Calibration + Compensation of Near-Field)



near-field effects

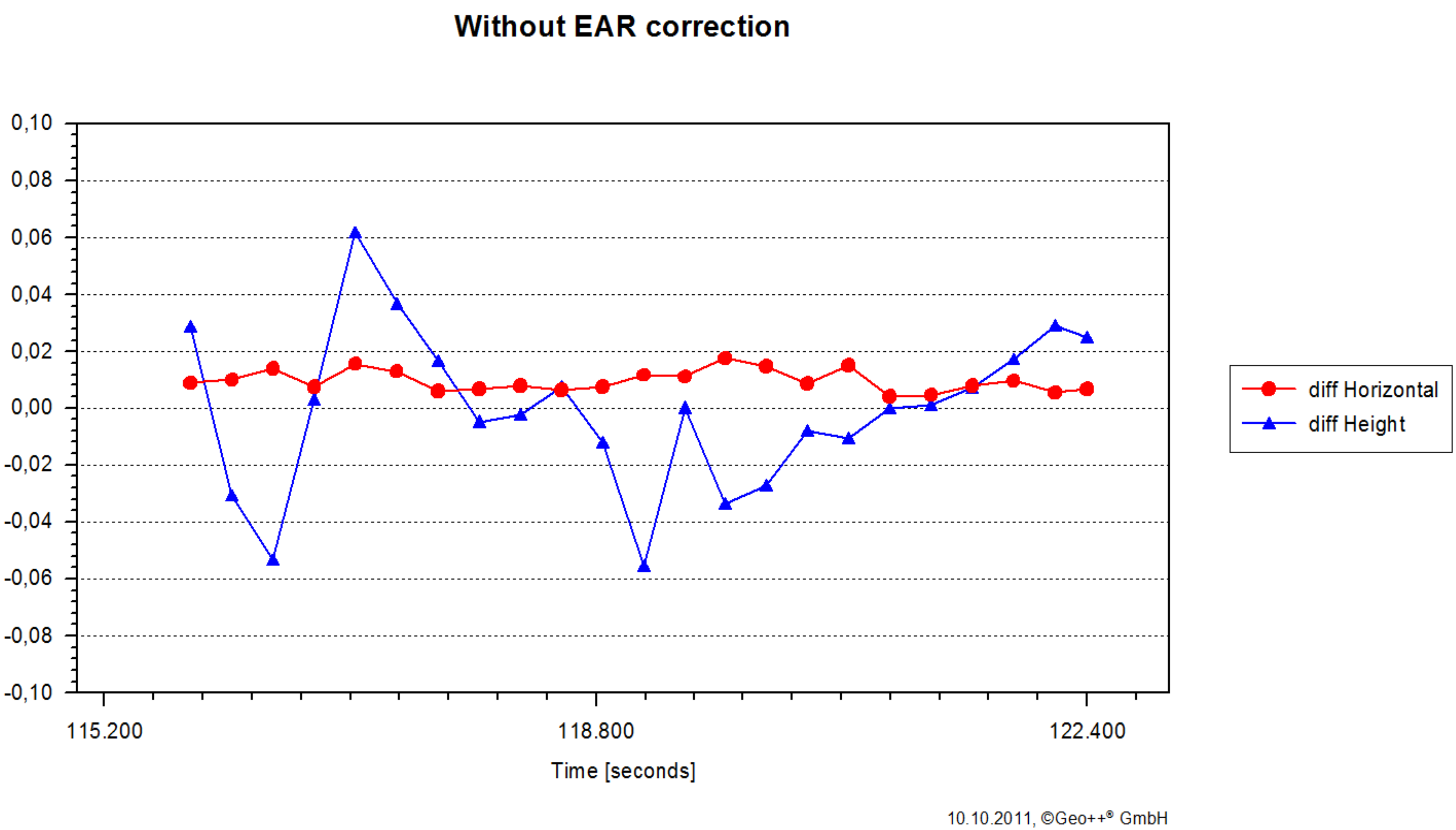
Corrected Near-Field effects

Verification Network (7 RS, Rover:HOFB, 5 Min. Solutions)



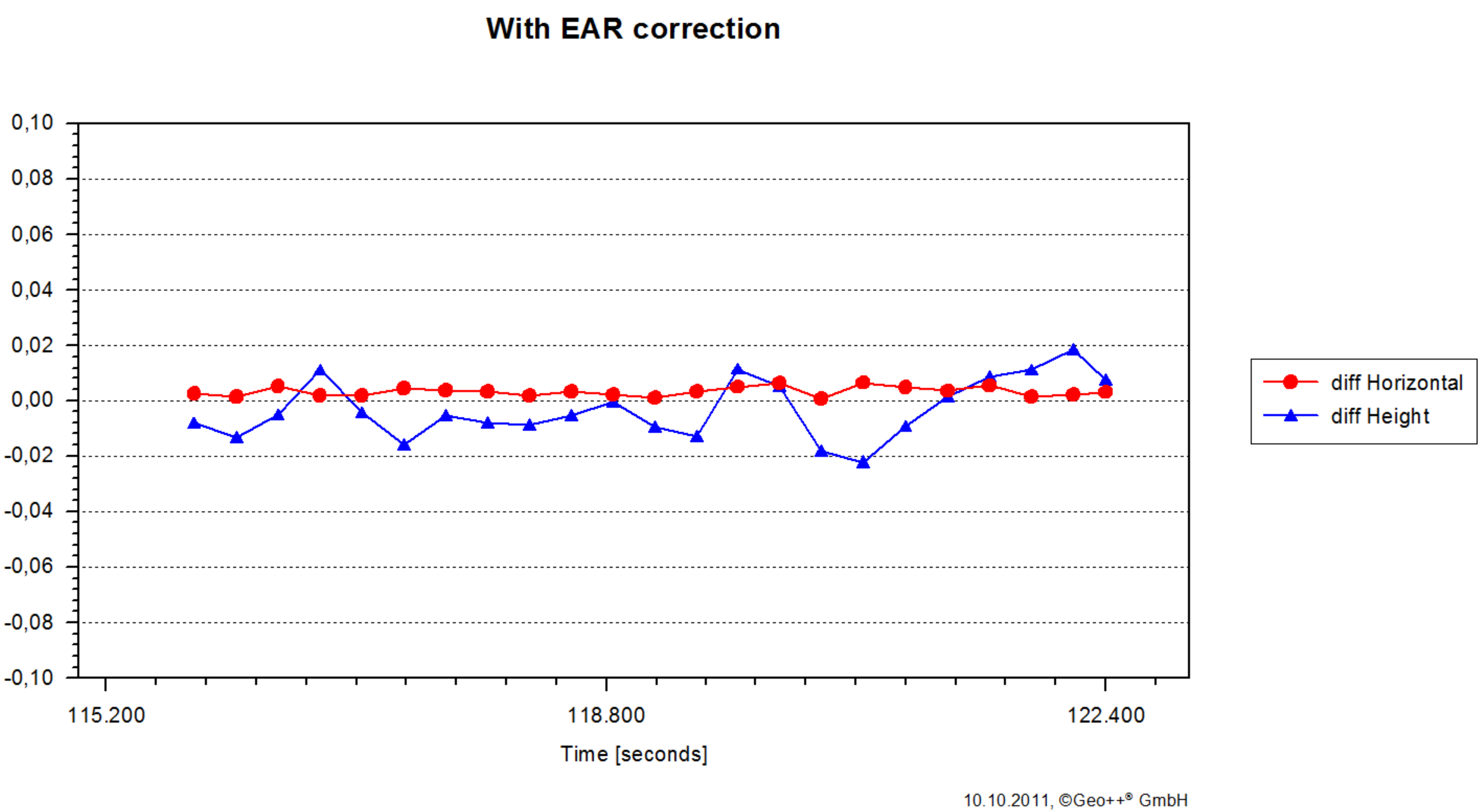
HOFB 5 Min. Solutions (incl. Troposphere Estimates)

Differences to Mean



HOFB 5 Min. Solutions (incl. Troposphere Estimates)

Differences to Mean



Summary/Outlook

- **NF** effects can significantly reduce performance of GNSS applications
- **in-situ NF calibration/compensation models** have been developed
  - combined approach using
    - robot calibration to obtain NF-free equipment
    - single site calibration utilizing NF free equipment (CaNF)
    - residual analysis in redundant GNSS CORS networks to compensate NF effects (CoNF)
    - combination of CaNF and CoNF to calibrate all network stations
  - NF correction and weighting models are obtained for all stations and signals
- **Method is ready for operational use**

thank you for your attention

References

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An Almost Philosophical Question ...

- obviously there are systematic errors through $MP_{near\text{-}field}$

Is it possible to determine GNSS heights without any systematic error?

- no, without considering $MP_{near\text{-}field}$
- yes, with taking $MP_{near\text{-}field}$ into account
  - with absolute $MP_{near\text{-}field}$ correction heights are free of systematic errors
- recommendation
  - analysis and assessment of additional strategies
  - avoiding $MP_{near\text{-}field}$