Absolute Receiver Antenna Calibrations with a Robot

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Motivation and Goal

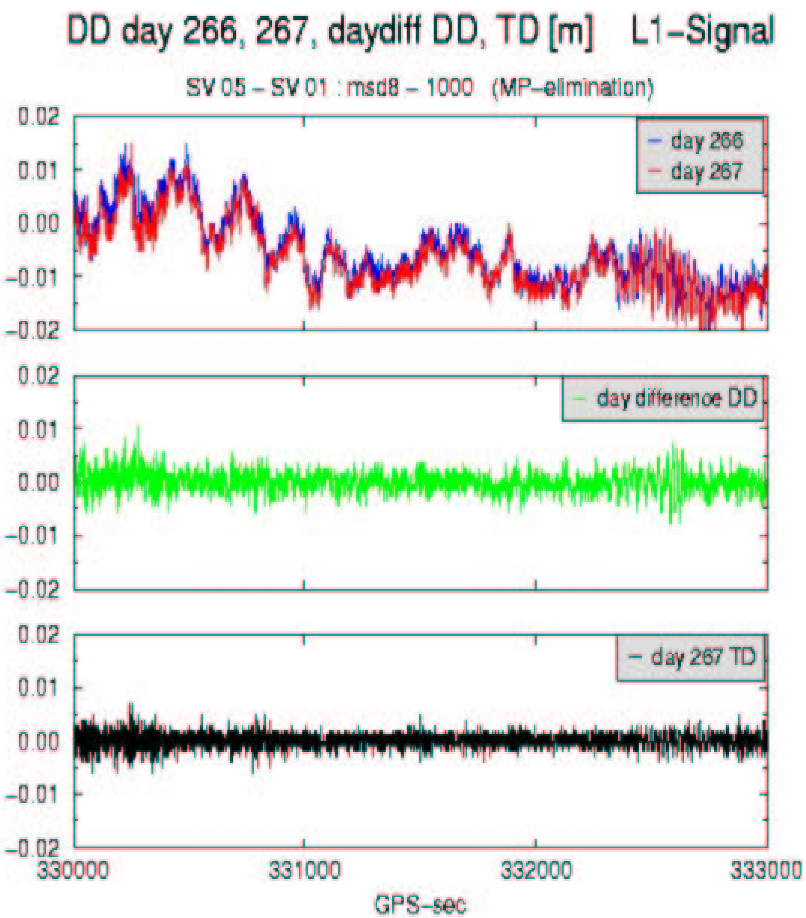
- problems with existing field calibration procedure
- problems with absolute chamber calibration results
- PCV urgently needed for mixed antenna type applications
  (e.g. RTK networks, engineering tasks)

- separation of multipath (MP) and phase variations (PCV)
- absolute PCV independent from reference antenna
- high resolution and precision for PCV
- site and location independent
- field procedure

Development of
Absolute PCV Field Calibration

- 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)
  - 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)

Development of Multipath Elimination Techniques and PCV Separation



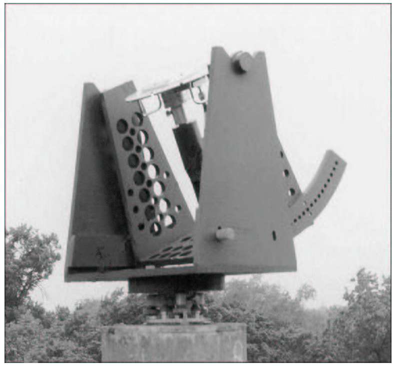
- siderial differences in post−processing
  - first approach
  - observation on two days
  - same geometry/environment

    eliminates MP
- short−term differences in real−time
  - operational procedure
  - same MP for subsequent epochs

    eliminates MP
- PCV reintroduced by orientation changes (rotations and tilts)

Development of Automated Antenna Mount

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



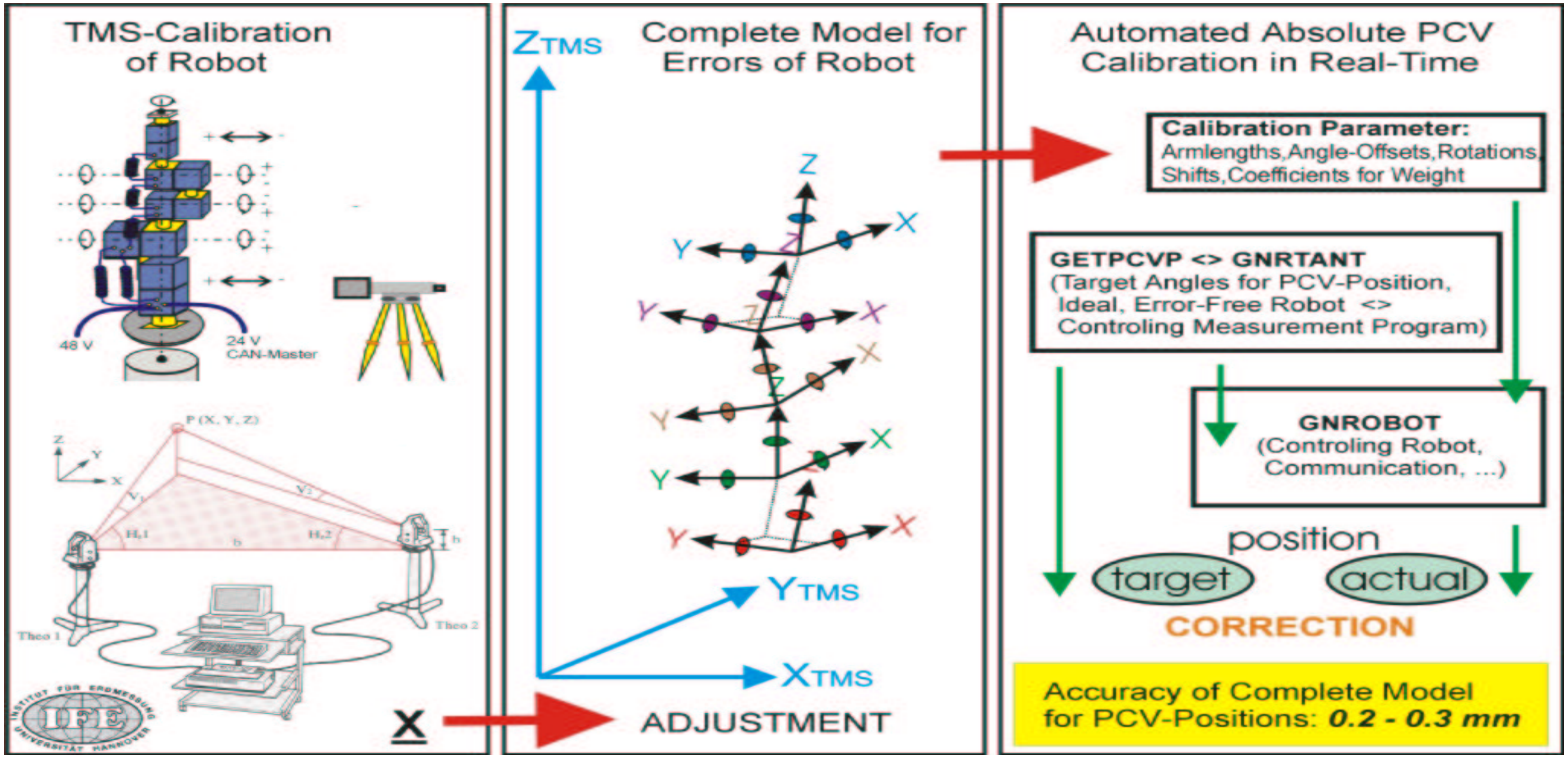
1996

1998

2000

Development of Robot Calibration Procedure

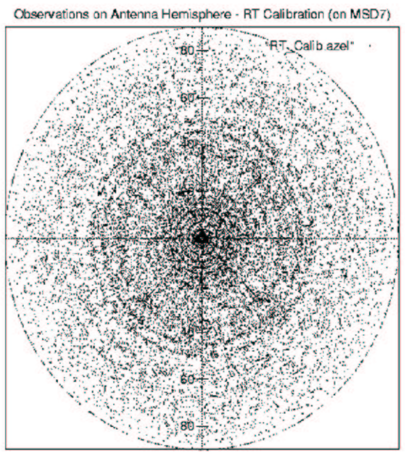
- corrections for robot required
- accuracy for antenna positions : 0.2 − 0.3 mm



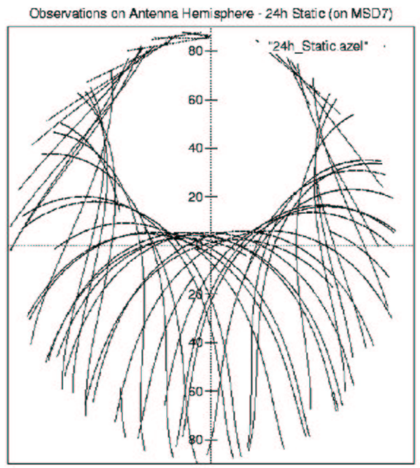
Details on Absolute PCV Field Calibration

- homogeneous coverage of antenna
  - 6000 − 8000 different positions
- dynamic robot guidance
  - depends on satellite constellation
  - optimizes observation time
- dynamic elevations mask
  - satellites with high elevation (>18°)
  - actual negative elevation (−5°) used

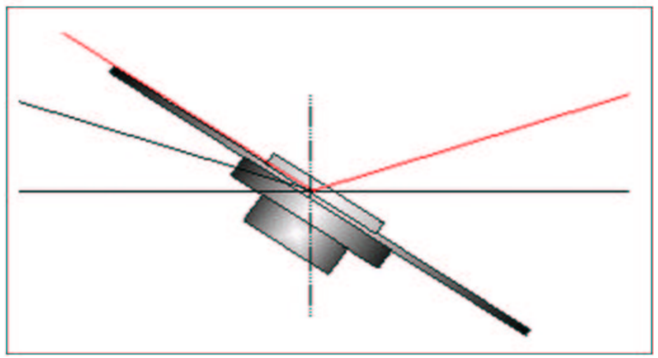
Coverage



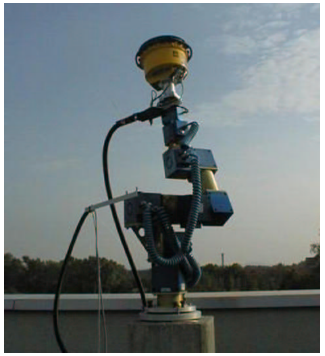
Absolute



Relative



Analysis of Operational Absolute PCV Field Calibrations

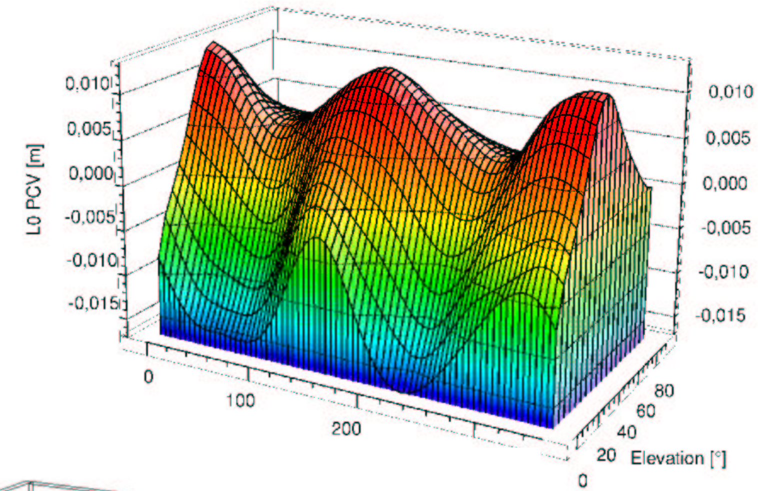


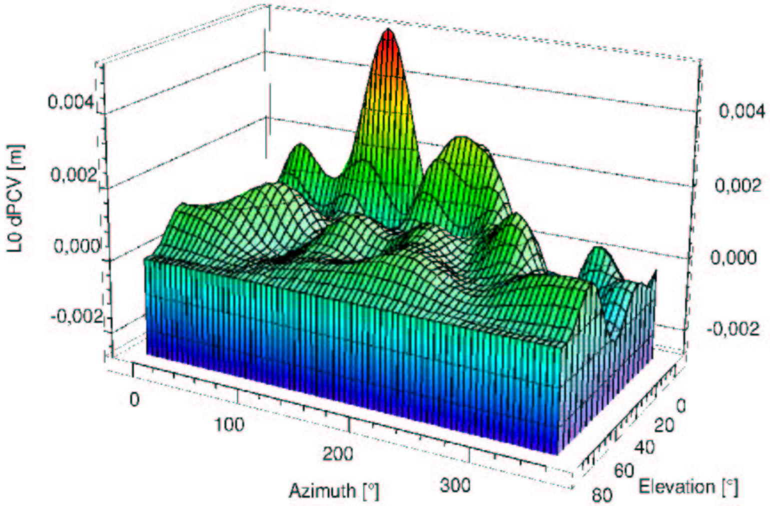
- different locations (Geo++, IfE)
- different times (days, seasons, ...)
- different weather (temperature, rain, snow, wind, ...)
- different robots (hardware, robot calibrations, performance, ...)
- different reference antennas (all major manufacturers)
- different GPS receivers (all major manufacturers)
- different north orientations
- different mounting on robot
- ...

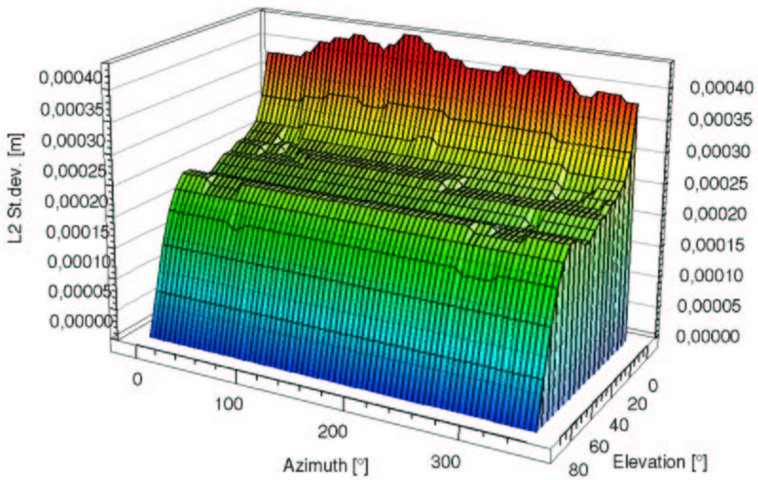
Repeatability and Accuracy of Absolute PCV Field Calibration

example LEIAT303

- absolute L0 PCV : −10 to 15 mm range
- std. dev. of L2 PCV : 0.2 to 0.4 mm range
- difference L0 PCV 5 month apart : 1 mm mean, except horizon





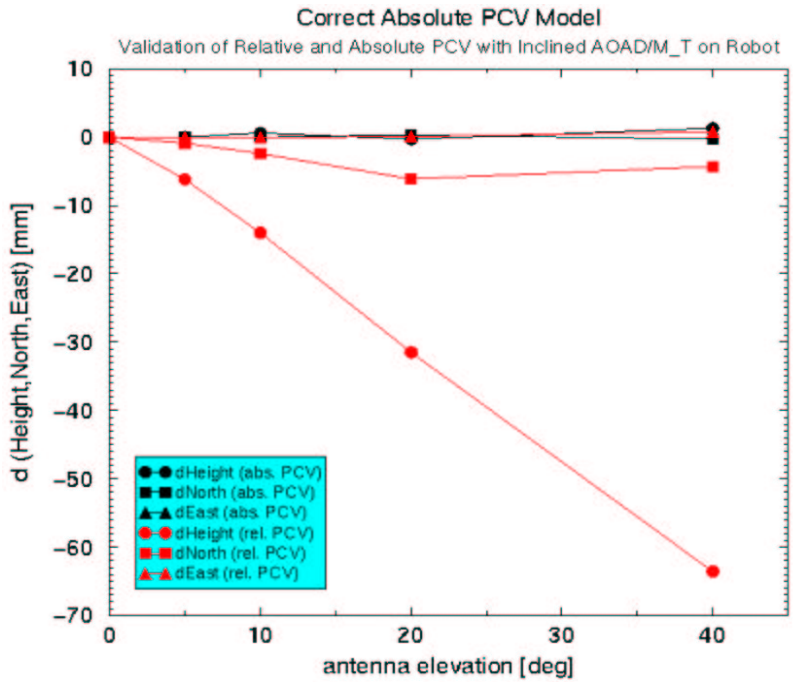


Characteristics of Absolute PCV Field Calibration

- absolute 3D offset
- absolute PCV
- PCV from (<) 0° to 90° elevation
- 0° to 360° azimuthal PCV
- simultaneous L1, L2 GPS and GLONASS PCV
- high resolution and precision
- free of multipath influence
- site and location independent
- at least two independent calibrations
- duration of several hours
- standard deviation 0.2−0.3 mm (1 sigma) for complete PCV (offset plus PCV)
- verification of accuracy through repeatability

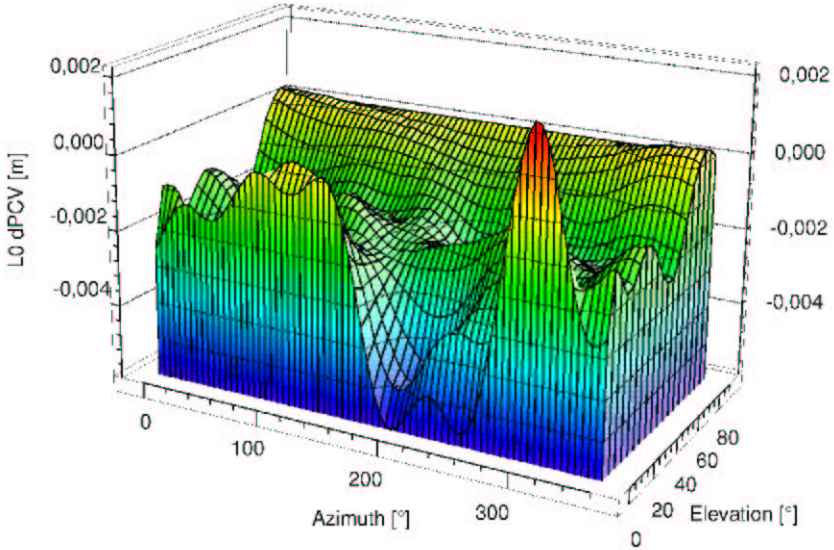
Verification of Absolute PCV

- concern “15 ppb scale” for global networks
- experiment simulating “large network”
  – inclined and rotated AOAD/M_T simulates geographical separation
  – no effects from atmosphere, orbits, satellite antenna using short baseline, true reference
- coordinates from 24 h data, L0 + tropospheric scale parameter
- proof by comparing absolute and relative PCV performance

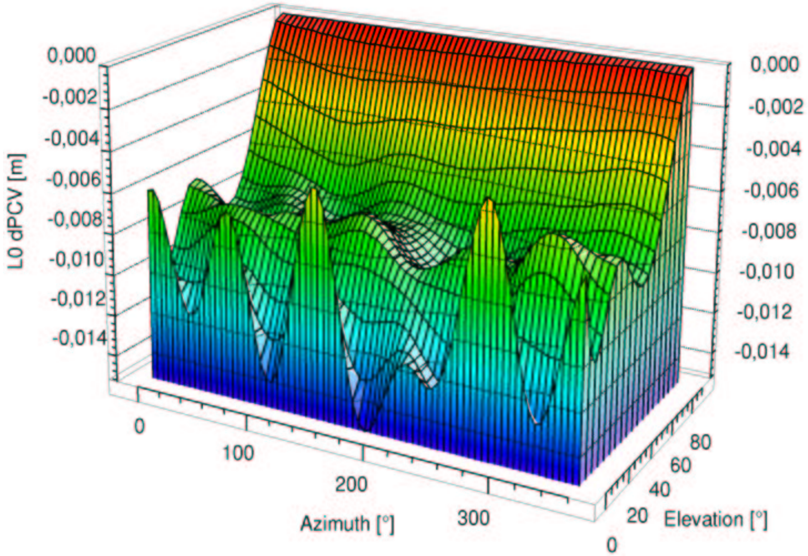


Effect of Radome Construction

- difference absolute L0 PCV LEIAT504 / LEIAT504 LEIS : −4 to 2 mm range

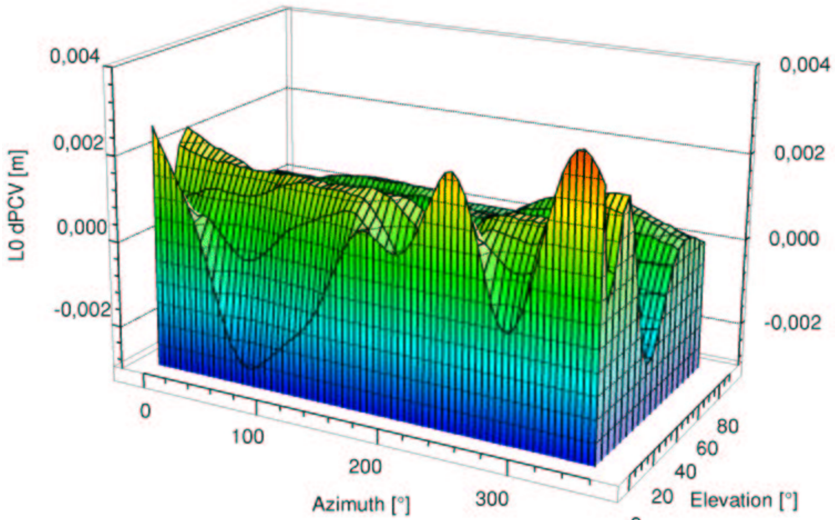


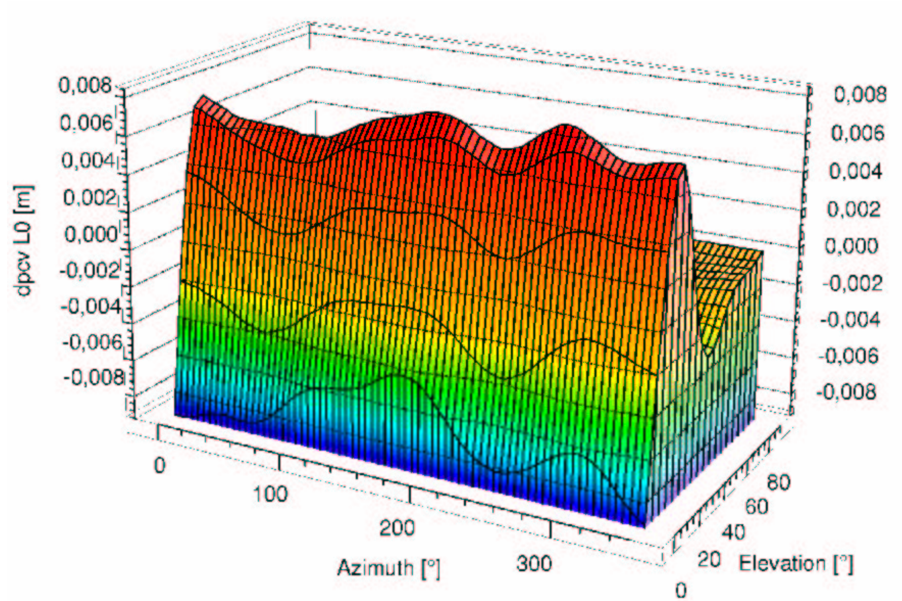
- difference absolute L0 PCV LEIAT504 / LEIAT504 SCIS : −14 mm range




Effect of Radome Construction

- difference absolute L0 PCV ASH700936M_E/ASH700936M_E SNOW : −2 to 4 mm range
- difference absolute L0 PCV TRM29659.00/TRM29659.00 TCWD : −8 to 8 mm range





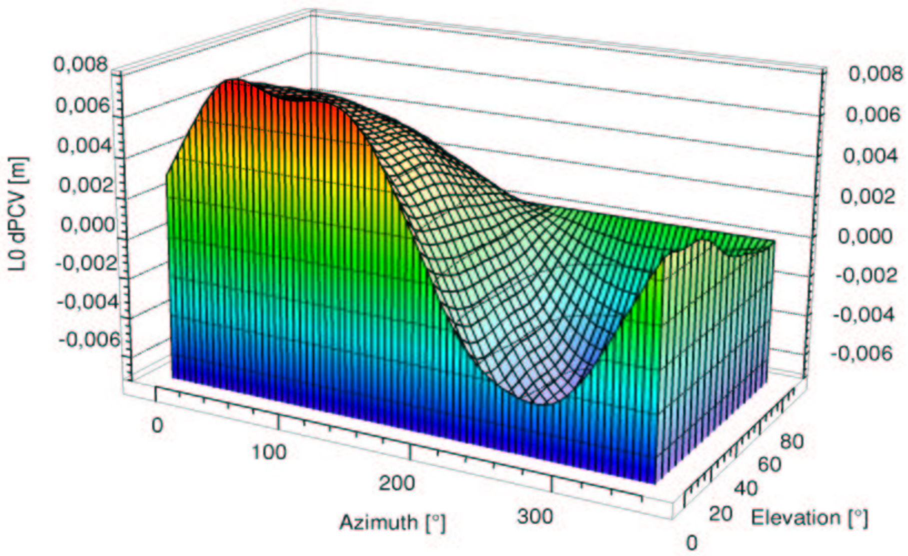
Individual or Type Mean PCV Correction

- individual calibration best choice
  - most antennas not accessible
  - option for new installations
- type mean suitable for other applications
  - simple procedure
  - uncertainty remains
- significant differences between antenna types observed
  - manufacturing series
  - assembling errors
  - outliers even for “Dorne Margolin Type” choke ring antenna

Example of Individual PCV Difference

- "Dorne Margolin Type" choke ring antenna
- best geodetic antenna type
- example of outlier
  - primarily L1 east offset
  - effect for L0 absolute PCV : −6 to 8 mm range
- different manufacturers
  - 1 outlier out of 10 antennas
  - 1 outlier out of 26 antennas

Typ −Individual Offset	*dNorth [mm]*	*dEast [mm]*	*dHeight [mm]*
L1	−0.2	−4.9	−1.0
L2	+0.1	+0.7	−0.1



Benefits of Absolute PCV Field Calibration and Correction

- high precision absolute PCV
- reliable azimuthal PCV
- separation of error components possible (e.g. station MP calibration, atmospheric parameter)
- unbiased absolute positioning
- mixed antenna type application possible (e.g. RTK networks)
- engineering application with inclined antennas (negative elevation)
- ...

Geo++ GNPCVDB Antenna Database

- type means from calibrated antennas
- rigorous adjustment using complete variance−covariance matrix of individual calibrations
- about 64 different antenna types (Dec. 2001)
  - 344 individual calibrated antennas
  - 1939 individual calibrations
- public information on e.g. PCV pattern shape, etc.
- license for access and use of absolute PCV
- http://gnpcvdb.geopp.de/

Acknowledgments

- The work of the project is funded by the German Ministry of Education, Science, Research and Technology (Bundesministerium für Bildung, Forschung und Technologie, BMBF) and the German Aerospace Center (Deutsches Zentrum für Luft− und Raumfahrt, DLR) under the grant 50NA9809.

References

- selected publications:

Wübbena, G., F. Menge, M. Schmitz, G. Seeber, C. Völksen (1996). A New Approach for Field Calibration of Absolute Antenna Phase Center Variations. Proceedings of International Technical Meeting, ION GPS−96, Kansas City, Missouri, 1205−1214.

Wübbena, G., M. Schmitz, F. Menge, G. Seeber, C. Völksen (1997). A New Approach for Field Calibration of Absolute Antenna Phase Center Variations. Navigation, Journal of The Institute of Navigation, Vol. 44, No. 2, 247−256.

Menge, F., G. Seeber, C. Völksen, G. Wübbena, M. Schmitz, (1998). Results of Absolute Field Calibration of GPS Antenna PCV. Proceedings of the International Technical Meeting, ION GPS−98, Nashville, Tennessee.

IfE, Geo++® (2000). AOAD/M_T Choke Ring Antenna Absolute Phase Variations, Results of Absolute PCV Field Calibrations at IfE and Geo++®. Internet Publication compiled by F. Menge and M. Schmitz, World Wide Web, http://www.ife.uni−hannover.de/~web/AOA_DM_T or http://www.geopp.com/gnpcvdb/AOA_DM_T.

Wübbena, G., M. Schmitz, F. Menge, V. Böder, G. Seeber (2000). Automated Absolute Field Calibration of GPS Antennas in Real−Time. Proceedings of the International Technical Meeting, ION GPS−01, Salt Lake City, Utah.

Böder, V., F. Menge, G. Seeber, G. Wübbena, M. Schmitz (2001). How to Deal With Station Dependent Errors − New Developments of the Absolute Calibration of PCV and Phase−Multipath With a Precise Robot. Proceedings of the International Technical Meeting, ION GPS−01, Salt Lake City, Utah.

Schmitz, M., G. Wübbena, G. Boettcher (2002). Tests of Phase Center Variations of Various GPS Antennas, and some Results. To be published in GPS Solutions, Vol. 6, No. 1.

- additional publications can be found under http://www.geopp.com/publikationen/lst_gpcv.htm

Global Ionosphere Maps Produced by CODE

Estimation of Elevation-Dependent Satellite Antenna Phase Center Variations

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Courtyard Marriott, Ottawa, Canada
10 April 2002

Contents

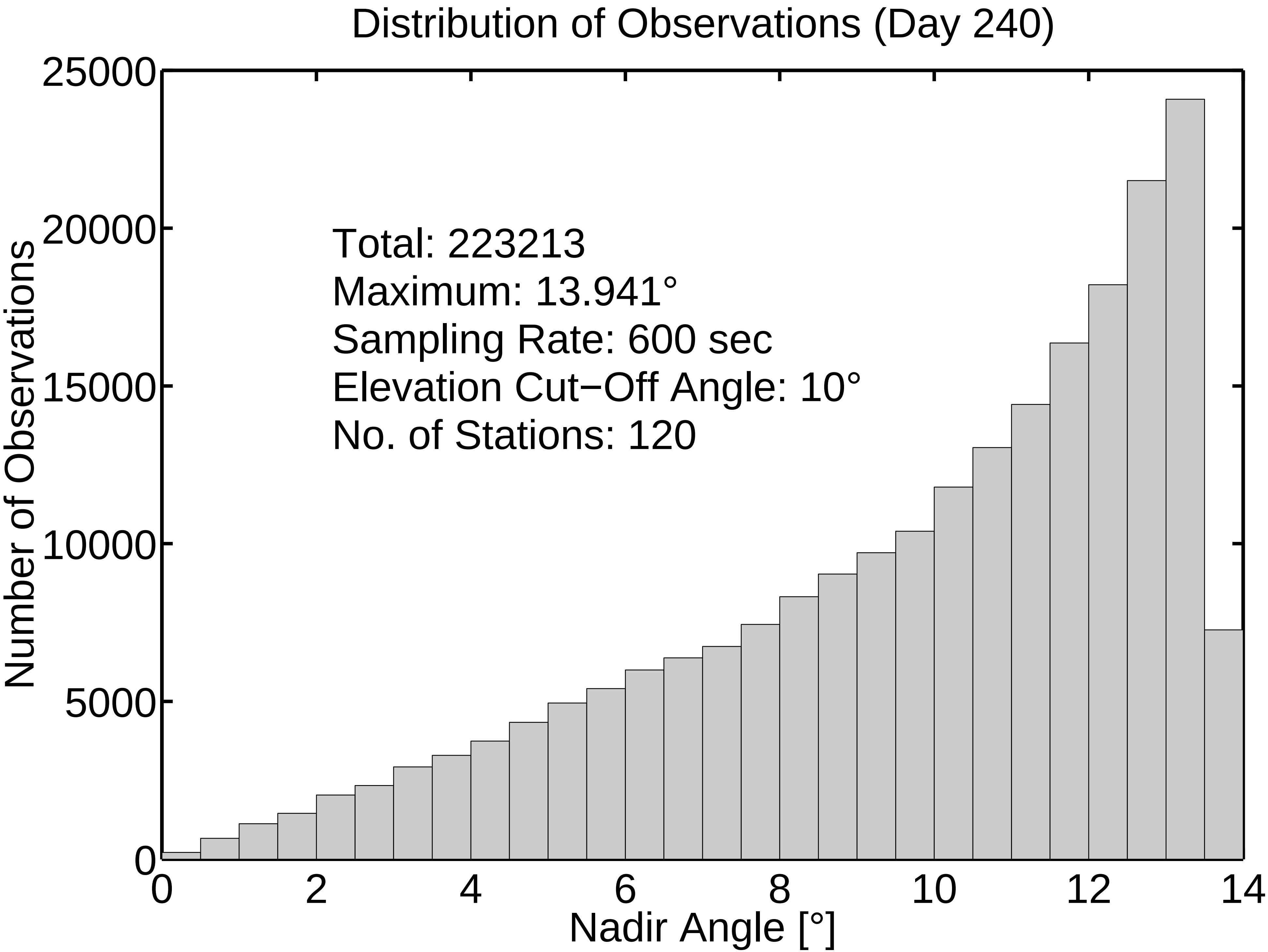
- **Introduction**
- **Estimation strategy**
- **Results**
- Repeatability between satellites of the same block
- Daily repeatability
- Differences between satellite blocks (Blocks II/IIA/IIR)
- Dependence on global scale
- Influence on global parameters (troposphere, earth rotation, orbits)
- **Conclusions**

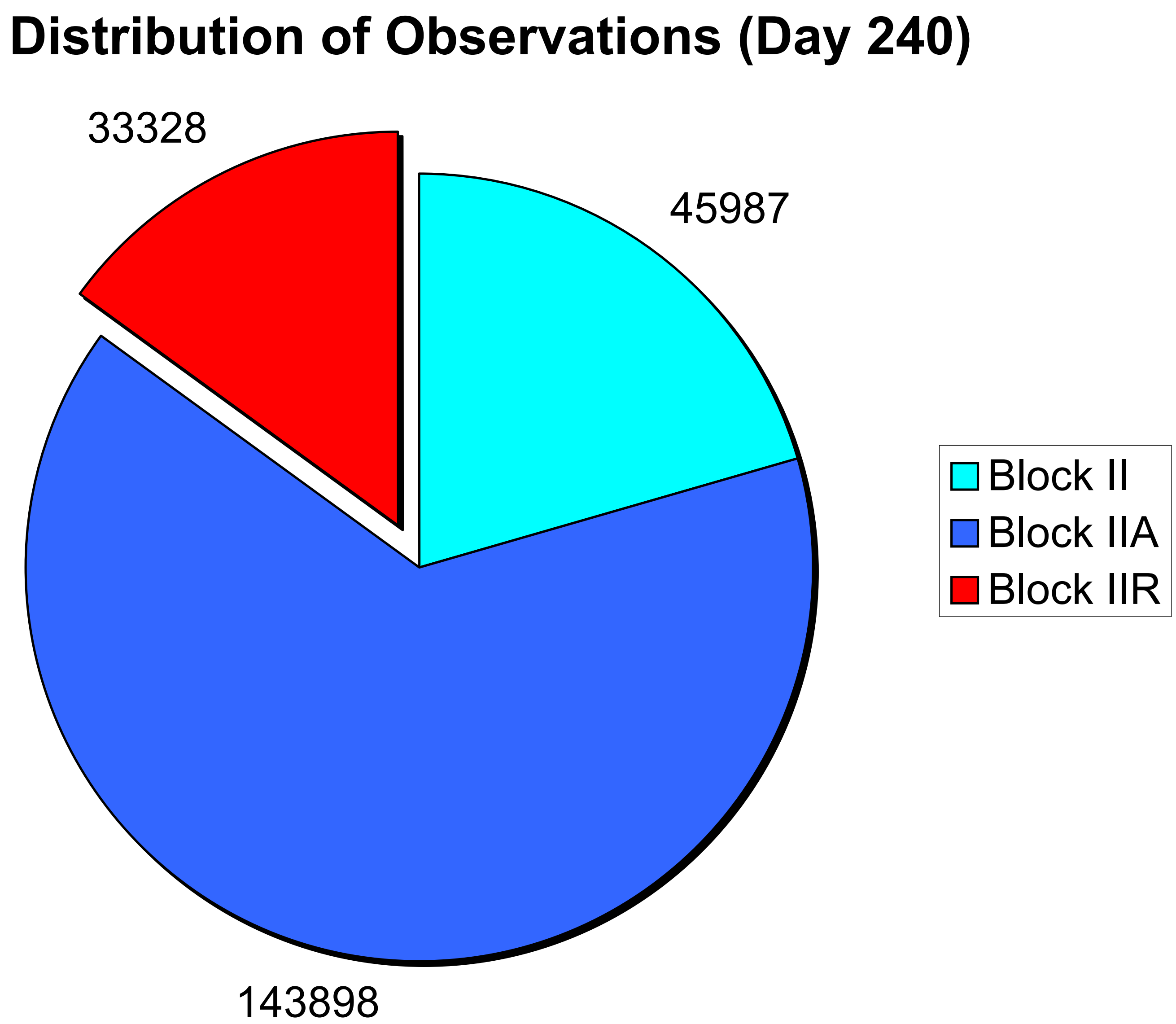
Introduction

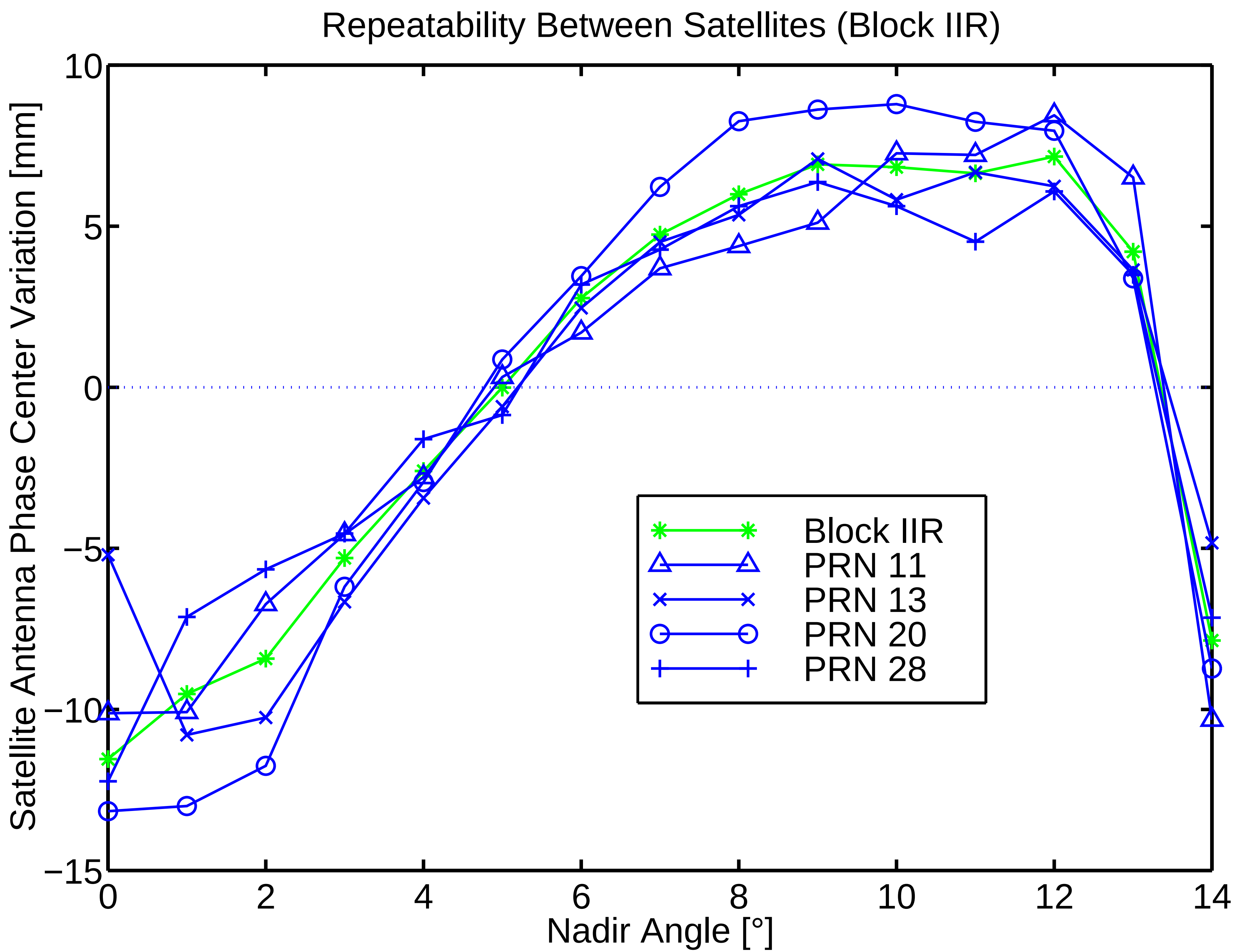
- Relative *receiver* antenna PCVs (elevation-dependent) are in use.
- Absolute *receiver* antenna PCVs are available from
  - anechoic chamber measurements and
  - absolute field calibrations (robot).
- **Problem:** Absolute PCVs cause a large terrestrial scale change of about 15 ppb in global GPS solutions.
- **Conclusion:** *Satellite* antenna PCVs have to be taken into account, because of the relationship between PCVs of the satellite antenna and the receiver antenna.

Estimation Strategy

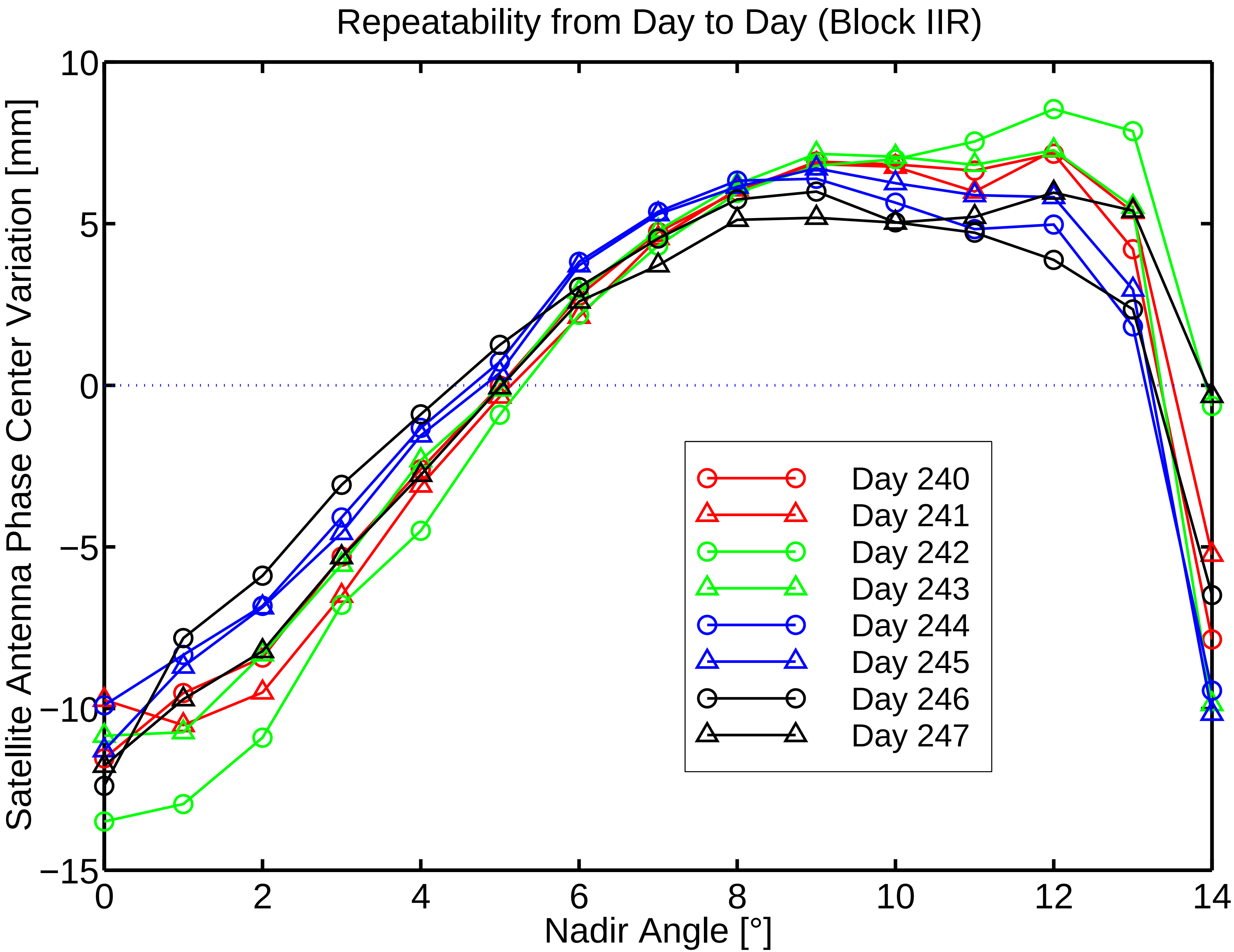
- IGS network (more than 100 stations)
- Daily solutions with estimation of satellite antenna phase patterns and all relevant global parameters
- Global scale fixed (by constraining station coordinates)
- Absolute receiver antenna PCVs from Hannover (IfE/Geo++)
- Polygon approach, 1°-resolution (0°-14°)
- Sum of all pattern values constrained to be zero (a mean variation is absorbed by the satellite clock)


Distribution of Observations (Day 240)
Total: 223213
Maximum: 13.941°
Sampling Rate: 600 sec
Elevation Cut−Off Angle: 10°
No. of Stations: 120
Number of Observations
Nadir Angle [°]
0
5000
10000
15000
20000
25000
0
2
4
6
8
10
12
14

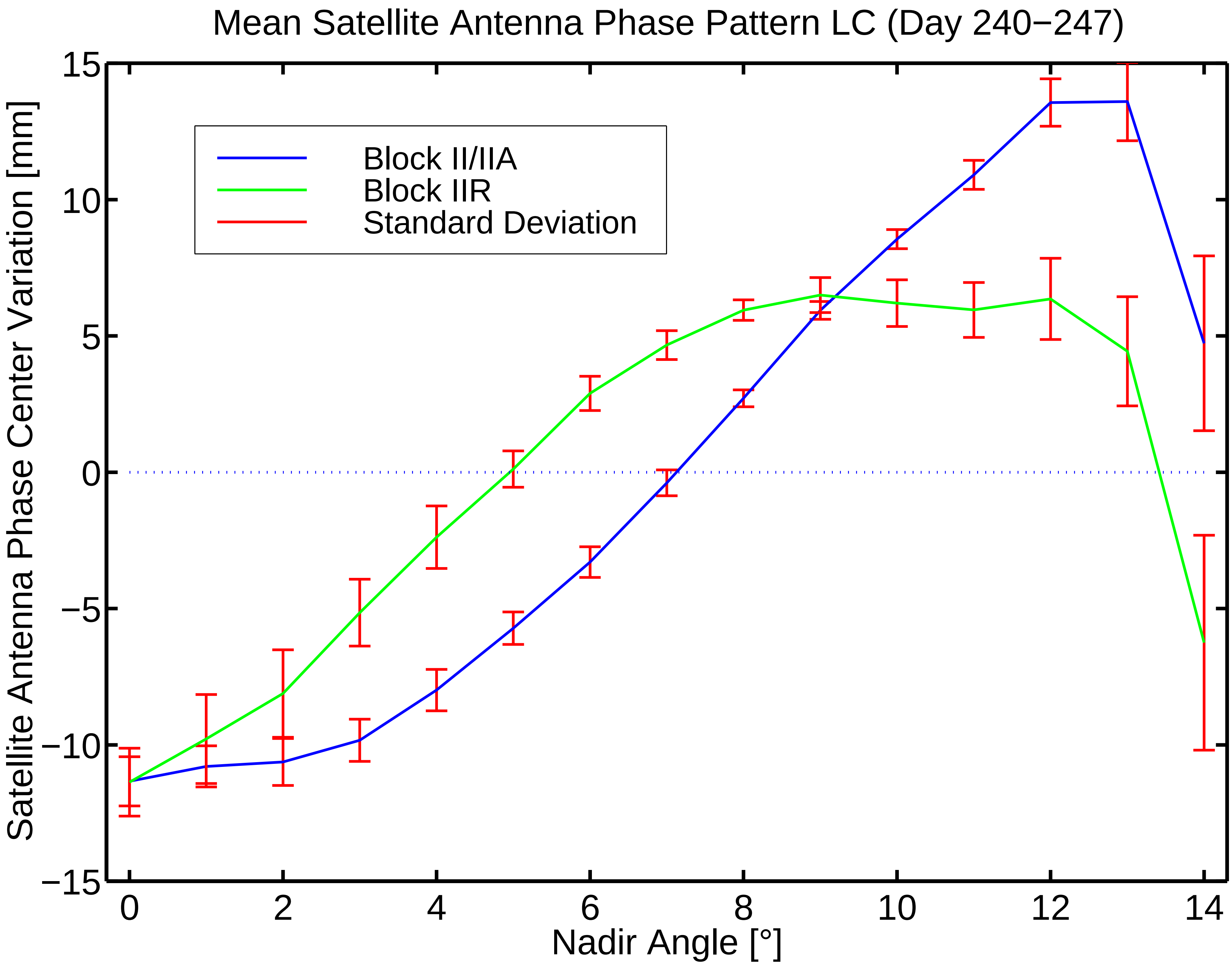

Distribution of Observations (Day 240)
33328
45987
143898
Block II
Block IIA
Block IIR

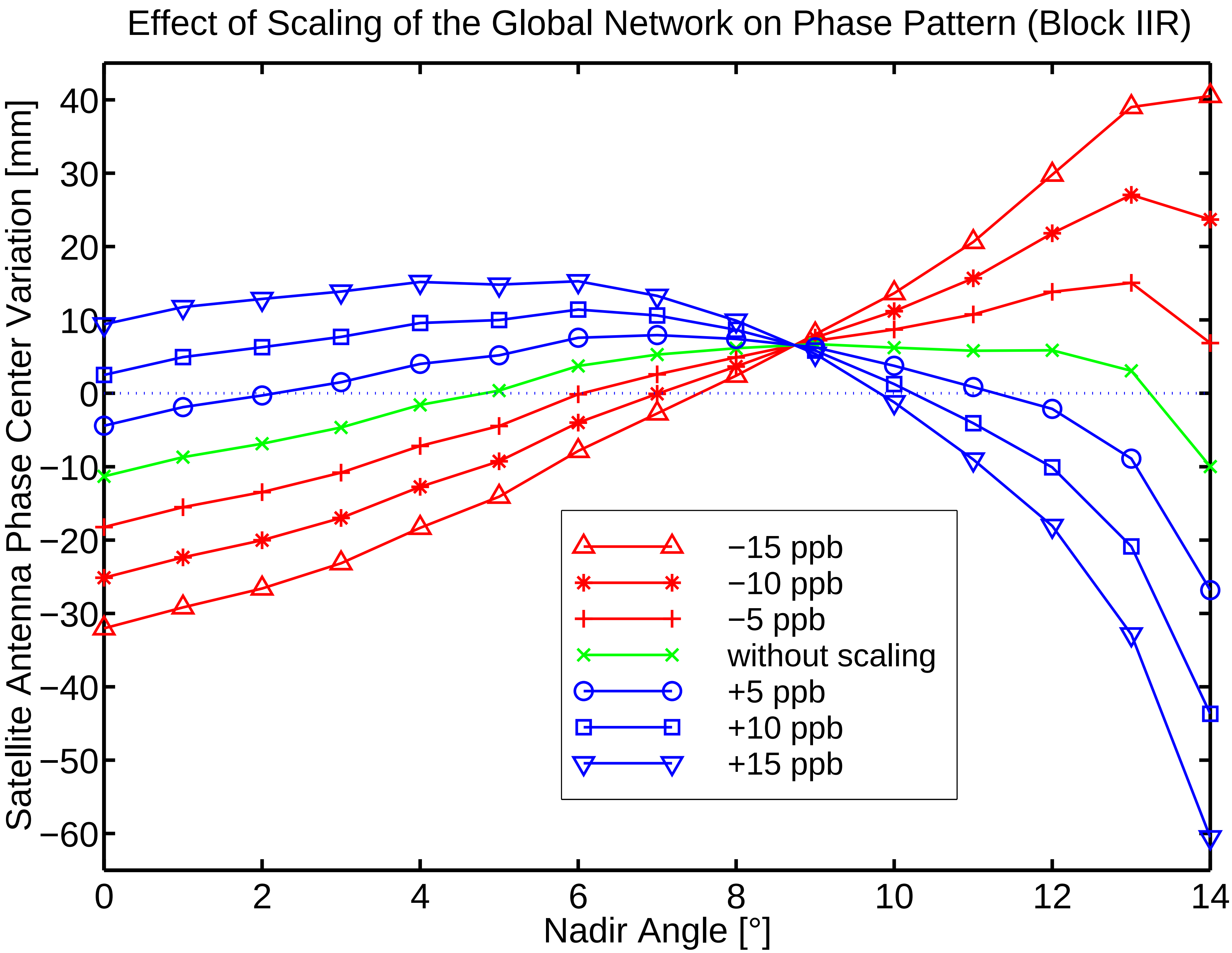


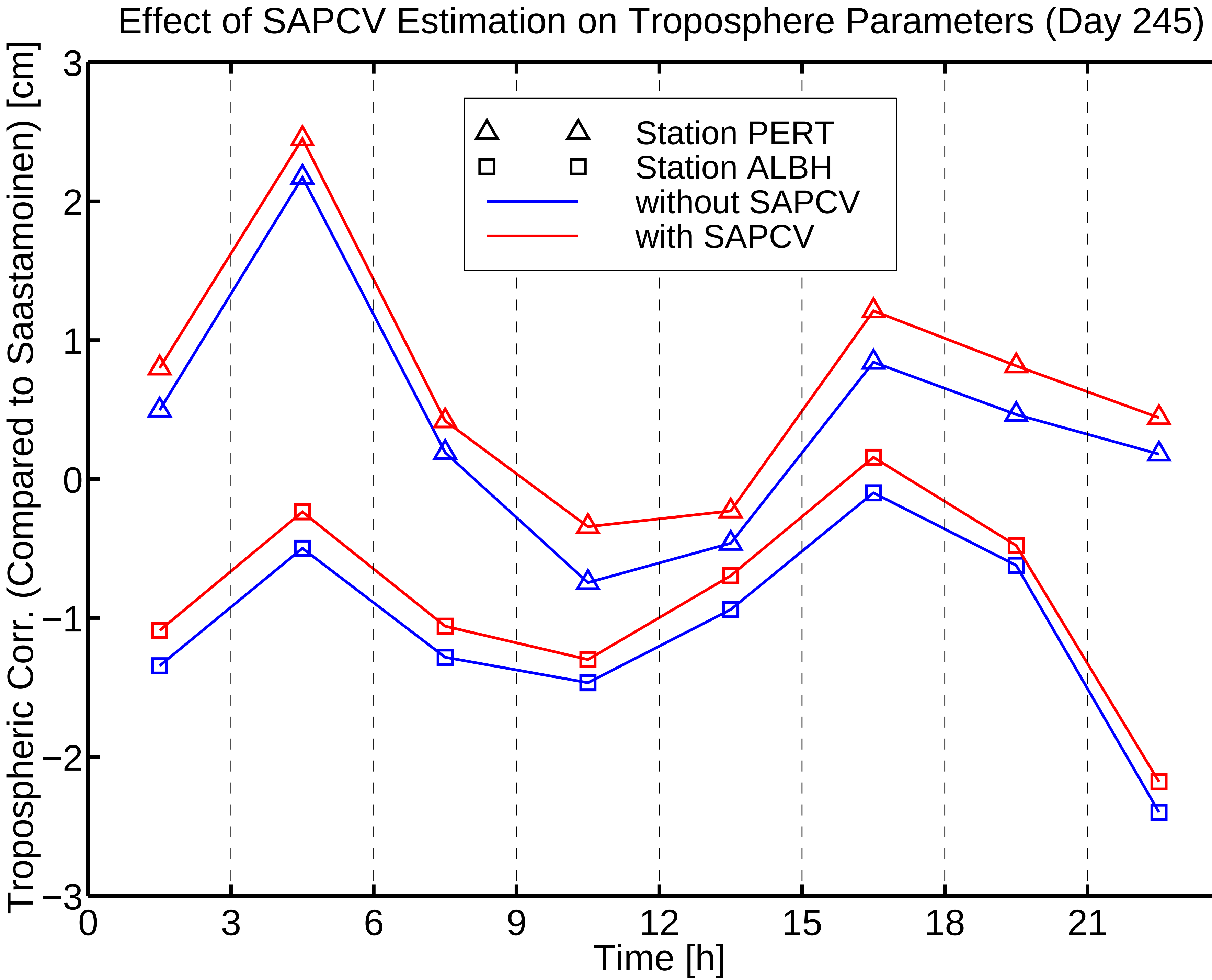
Repeatability Between Satellites (Block IIR)
Satellite Antenna Phase Center Variation [mm]
Nadir Angle [°]
10
5
0
−5
−10
−15
0
2
4
6
8
10
12
14
Block IIR
PRN 11
PRN 13
PRN 20
PRN 28

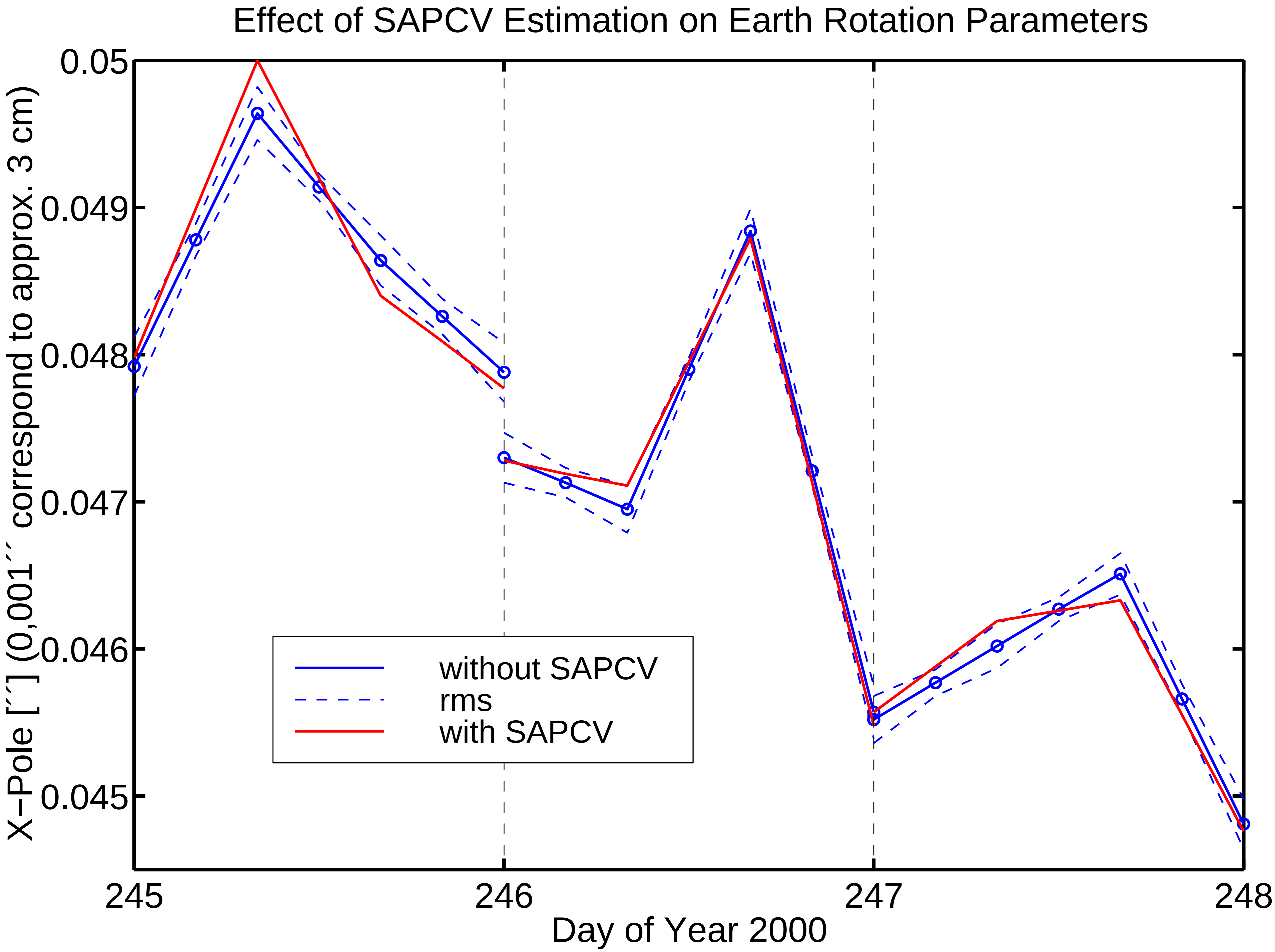


Repeatability from Day to Day (Block IIR)
Satellite Antenna Phase Center Variation [mm]
Nadir Angle [°]
10
5
0
−5
−10
−15
0
2
4
6
8
10
12
14
Day 240
Day 241
Day 242
Day 243
Day 244
Day 245
Day 246
Day 247


Mean Satellite Antenna Phase Pattern LC (Day 240−247)
Block II/IIA
Block IIR
Standard Deviation
Satellite Antenna Phase Center Variation [mm]
Nadir Angle [°]
15
10
5
0
−5
−10
−15
0
2
4
6
8
10
12
14


Effect of Scaling of the Global Network on Phase Pattern (Block IIR)
Satellite Antenna Phase Center Variation [mm]
Nadir Angle [°]
40
30
20
10
0
−10
−20
−30
−40
−50
−60
0
2
4
6
8
10
12
14
−15 ppb
−10 ppb
−5 ppb
without scaling
+5 ppb
+10 ppb
+15 ppb


Effect of SAPCV Estimation on Troposphere Parameters (Day 245)
Tropospheric Corr. (Compared to Saastamoinen) [cm]
Time [h]
Station PERT
Station ALBH
without SAPCV
with SAPCV
3
2
1
0
−1
−2
−3
0
3
6
9
12
15
18
21
24


Effect of SAPCV Estimation on Earth Rotation Parameters
X−Pole [´´] (0,001´´ correspond to approx. 3 cm)
0.05
0.049
0.048
0.047
0.046
0.045
245
246
247
248
Day of Year 2000
without SAPCV
rms
with SAPCV

Helmert Transformation between Orbits (With resp. Without SAPCV) for Different Satellite Blocks

	Day	DX [mm]	DY [mm]	DZ [mm]	RX [mas]	RY [mas]	RZ [mas]	SCALE [ppb]	RMS [mm]
Block II/IIA (24 Sat.)	240	-10	-19	2	-0,01	-0,07	0,01	-0,4	49,2
	241	-12	-21	1	-0,03	-0,10	-0,02	-0,4	47,9
	242	-7	-16	0	-0,04	-0,08	-0,03	-0,3	36,5
	243	-8	-19	3	-0,01	-0,04	-0,02	-0,4	40,4
	244	-8	-26	-3	0,02	-0,12	-0,11	-0,5	59,7
	245	-4	-23	-6	0,01	-0,14	-0,11	-0,4	55,1
	246	-11	-26	-6	0,01	-0,19	-0,04	-0,5	59,5
	247	-12	-27	-5	-0,02	-0,11	-0,13	-0,5	54,9
Block IIR (7 Sat.)	240	1	1	-3	0,02	0,00	-0,01	0,0	15,7
	241	0	1	-1	0,03	0,00	0,02	0,0	13,9
	242	0	1	-1	0,02	-0,02	-0,01	0,0	11,9
	243	0	1	-2	0,01	0,01	0,00	0,0	14,9
	244	1	1	-3	0,02	-0,02	-0,01	0,0	18,0
	245	-1	1	-2	0,03	-0,03	-0,01	0,0	16,8
	246	1	2	-3	0,03	-0,01	0,02	0,0	17,2
	247	2	2	-2	0,03	0,00	0,01	0,1	17,8

Conclusions

- Satellite antenna PCVs estimable
- Repeatability (daily, between satellites): ~ 1-3 mm
- Different patterns for Block II/IIA and Block IIR
- Systematic effect on Block II/IIA orbits:
  rms ~ 5 cm, Y-component of the geocenter ~ 2 cm
- Systematic effect on tropospheric delay: ~ 3 mm
- Consistent absolute PCVs now available for receivers and satellites

Multipath characteristics of GPS signals as determined from the Antenna and Multipath Calibration System (AMCS): Preliminary results

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Harvard-Smithsonian Center for Astrophysics

P. Jarlemark
SP Swedish National Testing and Research Institute

B. Corey, A. Niell
MIT/Haystack Observatory

C. Meertens, V. Andreatta
UNAVCO/UCAR Facility

Overview

- Description of the AMCS
- Some Preliminary Results
- Conclusions and Future Work

Park et al., (in preparation)

AMCS Accuracy Goal and Method

- **Goal**: Develop an *in situ* method for absolute calibration of site-dependent GPS phase-measurement errors such as scattering, multipath and unmodeled antenna phase variations ("SMA effects") with an accuracy of 1 mm (each frequency).

- **Method**: Form single phase differences between a GPS receiver connected to a GPS antenna to be calibrated and a second GPS receiver connected to an antenna free of SMA effects.

Components of the AMCS

- High-gain, multipath-free, 3-m diameter parabolic antenna
- GPS test antenna to be calibrated
- Two GPS receivers

Unique Strengths of the AMCS Method

- Current multipath reduction/calibration methods used include microwave absorber, relative field calibrations, anechoic chamber, mechanical robot, and data filtering.

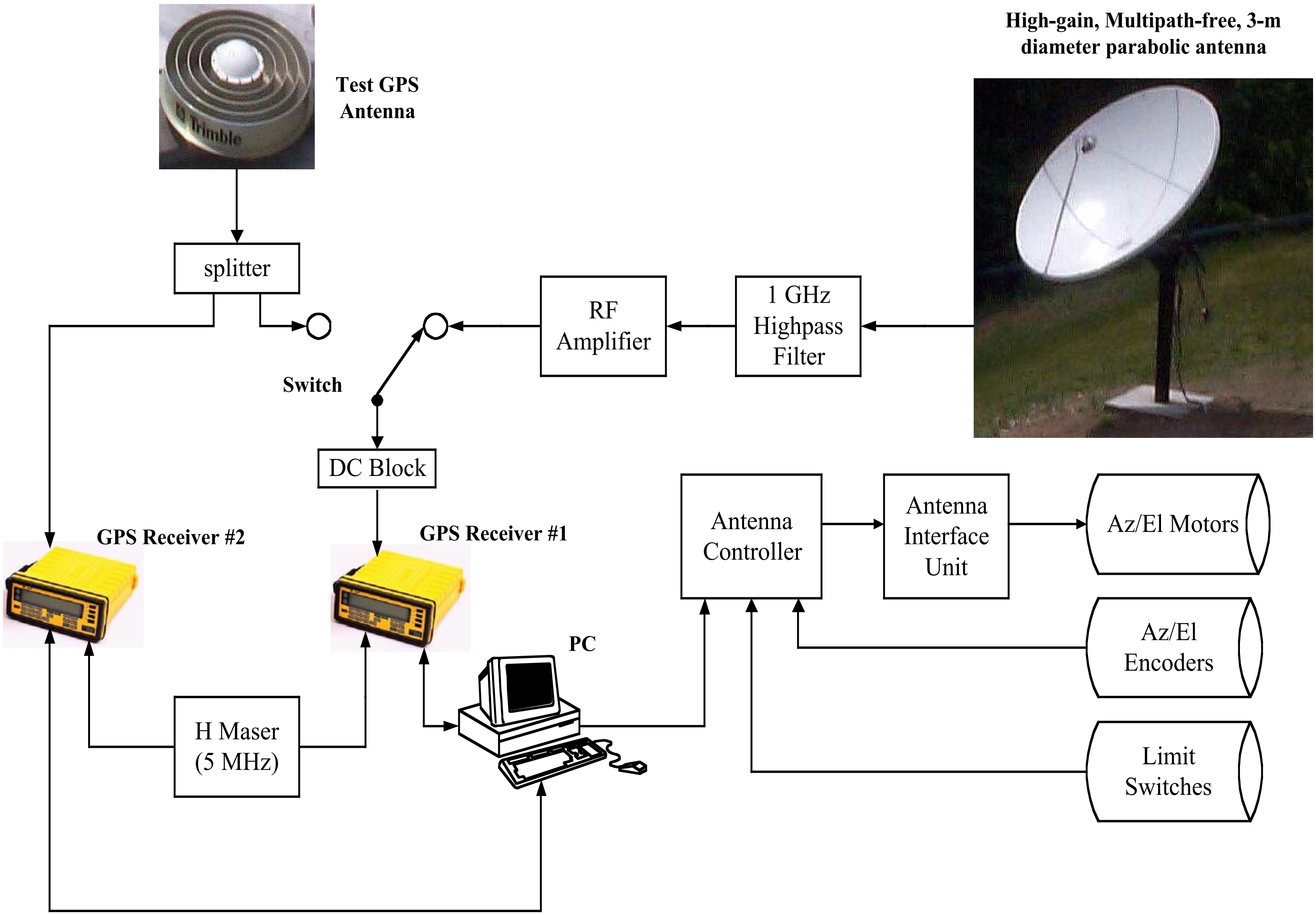
- The AMCS enables us to accomplish three types of studies that are not possible with any other method:

  – In situ, absolute site calibration

  – Understand the sources of SMA effects, their dependence on weather and environment, and their time variability

  – Development and testing of improved antennas and understanding of site effects

Block diagram of the AMCS

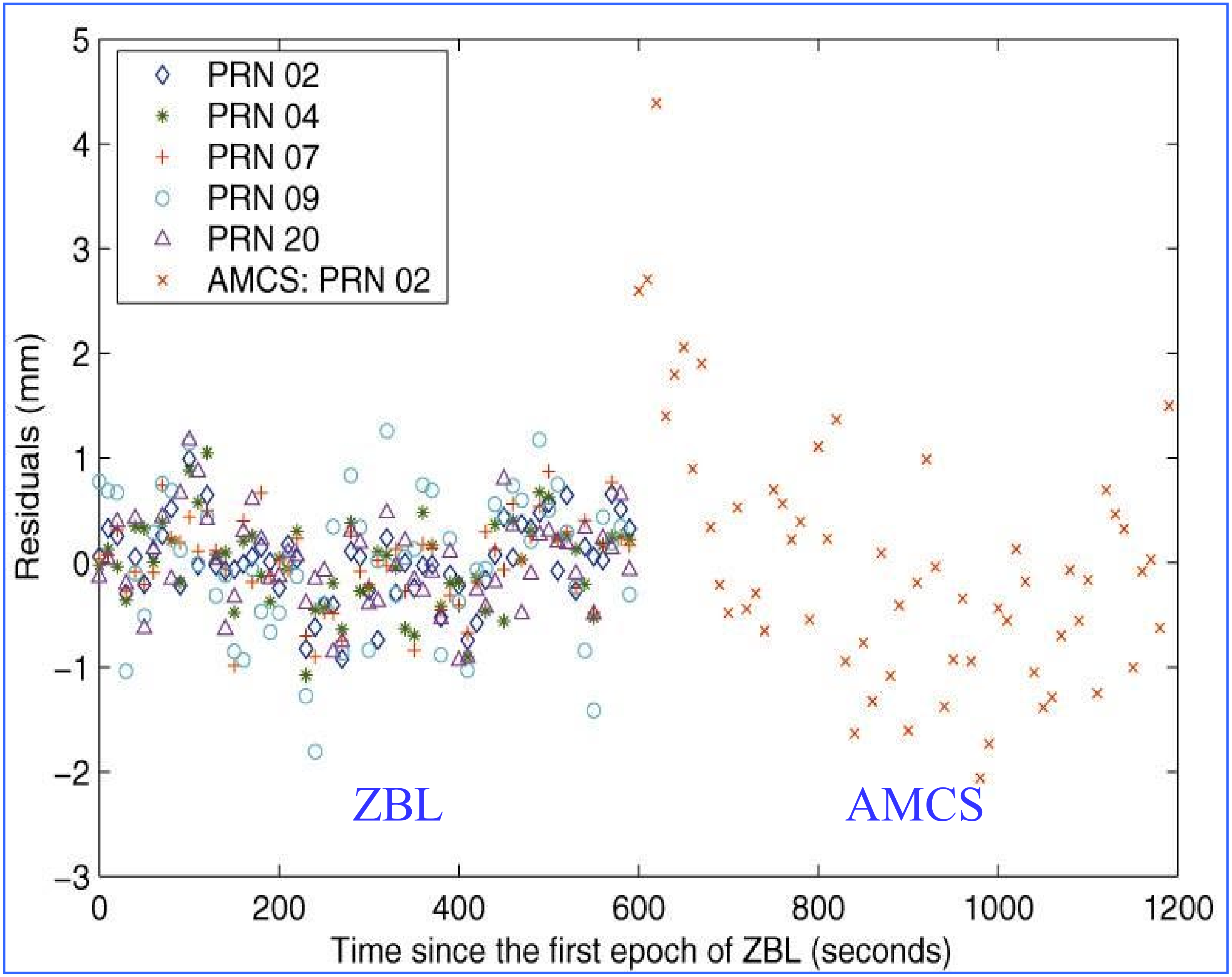


Modes of Operation

- Zero-Baseline (ZBL) Calibration Mode
  - Both receivers collect data from the GPS test antenna
  - ZBL-mode data is processed to estimate a clock synchronization error and a phase offset of each satellite, which will be used in AMCS-mode data processing as fixed parameters

- AMCS Mode
  - **Static** (Calibration)
    - The parabolic antenna is stationary, pointing toward a certain direction, and the target GPS satellite drifts in and out of the antenna main beam
  - **Tracking**
    - The parabolic antenna tracks the target GPS satellite and its pointing direction is updated at each observation epoch

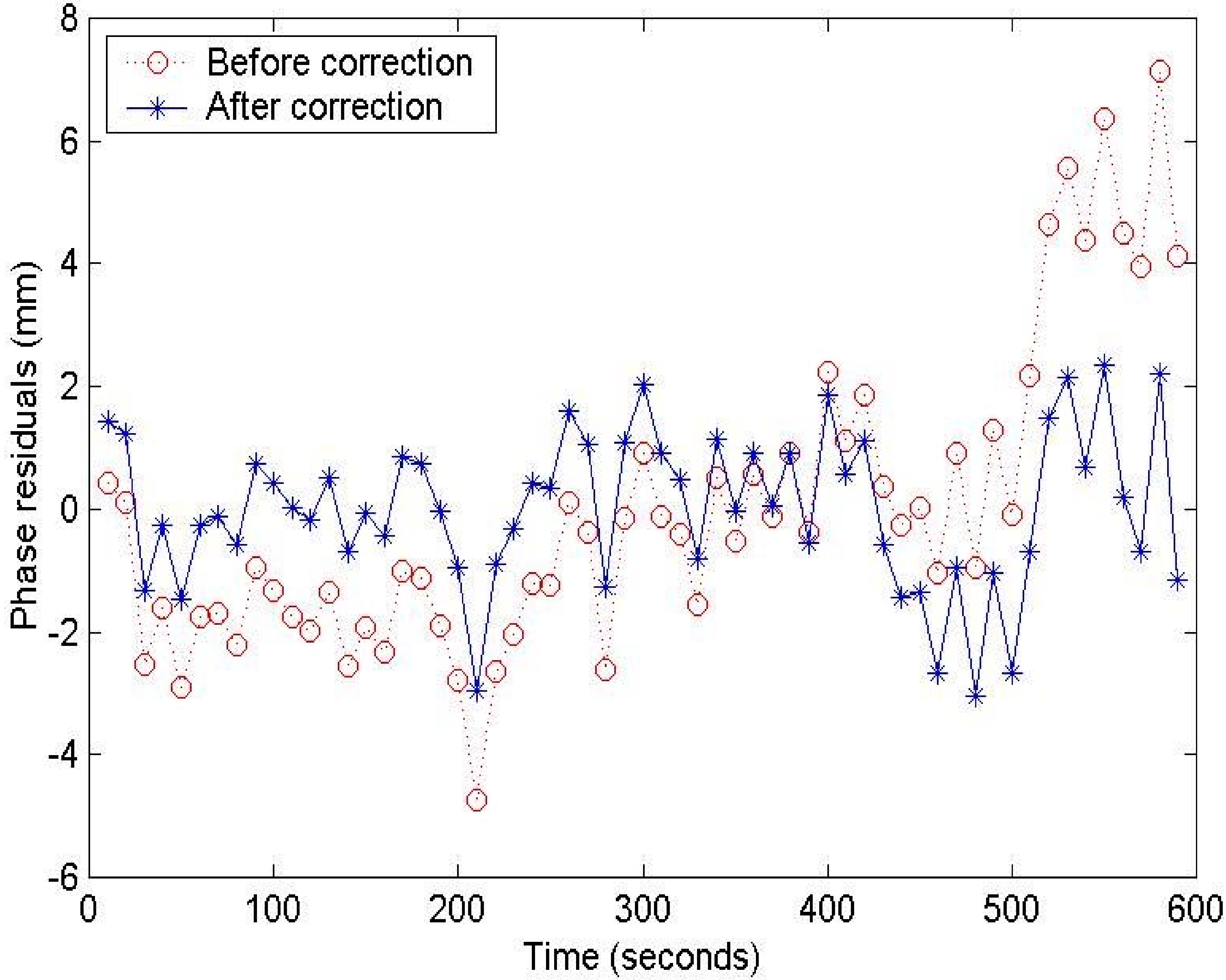
L_1 Phase Residuals (ZBL/AMCS-static)



Analysis of Residuals (ZBL/AMCS-static)

- ZBL-mode residuals: RMS ~0.5 mm
- AMCS-mode (static) residuals: RMS 1 - 3 mm
  - *Highly systematic variations*
    - Parabolic antenna pointing offset errors
    - Baseline error
    - Parabolic beam pattern errors
    - Low Signal-to-Noise Ratio (SNR) in the AMCS-mode data collection

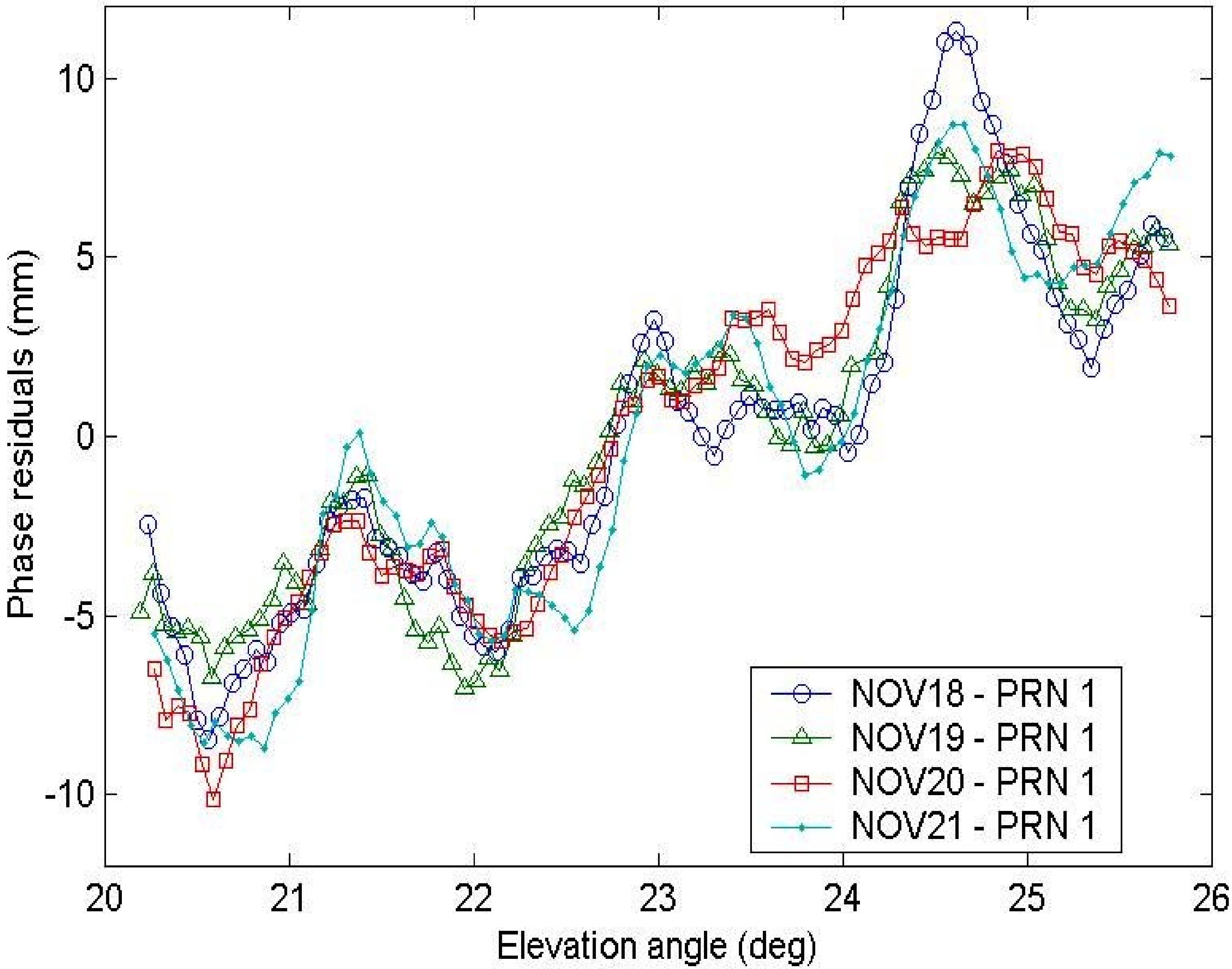
Correction of Baseline-dependent Error



AMCS-tracking Analysis

- Observing schedule:
  - 10-minute ZBL-mode
  - 10-minute AMCS-mode
  - Steer the parabolic antenna every 10 seconds
- Track the same satellite for several consecutive days
- Track different GPS satellites
  - Elevation angle: high, medium, and low
  - Azimuth angle: extensive coverage

L_1 Phase Residuals (AMCS-tracking)



Results of AMCS-tracking Analysis

- Effects are low-amplitude (~5 mm)

- Effects vary extremely rapidly in elevation angle
  - periodicity with variations of $\sim 1^{o}$ of elevation angle
  - periodicity is not very regular

- Effects are fairly repeatable from day to day

  but they can also vary by amounts large with respect to the AMCS measurement uncertainty of 1mm

- Effects are very sensitive to azimuth and time of day

  perhaps due to moisture on reflecting surfaces, temperature, or both.

- Amplitude variations of multipath effects are typically larger at lower elevation angles

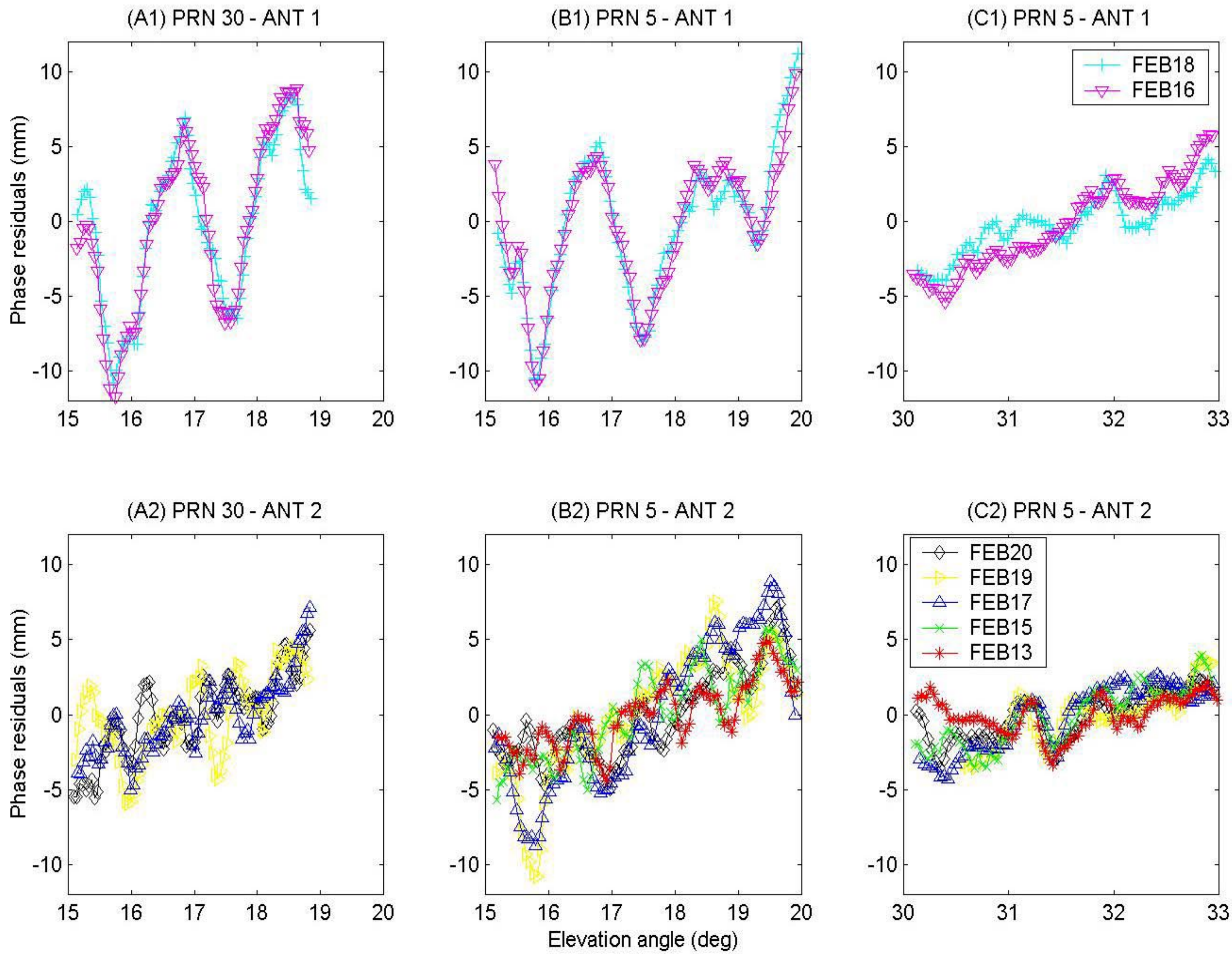
Second GPS Test Antenna

- Objective: are the observed effects due to multipath?

- Installed a second GPS antenna
  - Same antenna type and hardware
  - Reduced multipath environment
  - Microwave absorber

- Observations: 10 days in February 2002

- Compare phase residuals between GPS antennas



(A1) PRN 30 - ANT 1
(B1) PRN 5 - ANT 1
(C1) PRN 5 - ANT 1
FEB18
FEB16
(A2) PRN 30 - ANT 2
(B2) PRN 5 - ANT 2
(C2) PRN 5 - ANT 2
FEB20
FEB19
FEB17
FEB15
FEB13
Phase residuals (mm)
Elevation angle (deg)

Second Test Antenna (cont'd)

- GPS antenna in **higher multipath** environment
  - Residuals are more repeatable from day to day
  - Larger amplitude variations
  - Larger signal amplitude at low elevation

- GPS antenna in **lower multipath** environment
  - Residuals are less repeatable from day to day
  - Smaller amplitude variations
  - Amplitude rather independent of elevation angle

Summary and Conclusions

- Description of AMCS

- ZBL-mode phase residuals are ~0.5 mm (RMS)

- AMCS-mode phase residuals
  - Measured absolute SMA effects
  - High spatial resolution (sub-degree)
  - Accuracy is ~1 mm

  - SMA effects are:
    - Low-amplitude (~5 mm)
    - High-frequency (periodicity with variations of 1^{o} elevation angle)
    - Fairly repeatable from day to day
    - Very sensitive to azimuth angle and time of day

Future Research and Calibration

- **Open questions**:
  - How dependent are these effects on environmental conditions?
  - Can an accurate and standard set of calibrations be obtained for a GPS site?
  - What is the ultimate limitations that these effects place on the accuracy of (geodetic and geophysical) estimates obtained from GPS data?

- **Quantitative answers:**
  - Construct a second, field deployable AMCS:
    - Side-by-side tests for accuracy assessment
    - Characterization of SMA effects at various GPS test sites
    - Deliberate introduction of SMA effects for model applicability
    - Time-series analysis of GPS analyses with/without SMA corrections