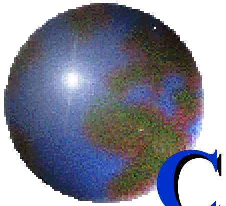
Some Metrological Issues of GNSS Positioning: Case Study for the Czech Republic



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VÚGTK

Technologická agentura České republiky

POSITION

- Relation of geometric elements and figures to a reference geometric structure (coordinate system)
- Coordinate system is realized as a n-tuple of lines with defined directions and with one common point (origin)
- Position is expressed in coordinates
- Coordinates are n-tuples of numbers expressing distances from the point to each of coordinate lines; they uniquely determine the position of a point (or other geometric element) on a manifold (e.g. In Euclidean space)

DEFINITIONS

DEFINITION OF THE UNIT OF LENGTH

- The base unit in the International System of Units (SI) is the metre defined as „the lengths of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second“

DEFINITION OF THE UNIT OF TIME

- Second (s) – since 1967 defined as the second of the International Atomic Time – 9,192,631,770 periods of radiation emitted by a Caesium-133 atom in the ground state

PRINCIPLE of GNSS-based POSITIONING

- GNSS receivers directly measure (besides digital analysis of the signal, mathematical processing of its sampling etc.) time intervals between modulation codes (P, C/A) and carrier phases
- Results of the mathematical processing are „measured“ quantities – coordinates or coordinate differences
- GNSS deals directly with the units of lengths defined in the International System of Units (SI)

METROLOGY (1)

- Metrology as defined by the BIPM is „the science of measurement“; it includes all theoretical and practical aspects of measurements at any level of uncertainty in any field of science and technology
- Measurement - assignment of numbers to objects or events
  - level of measurement (includes magnitude)
  - dimensions (units)
  - uncertainty
- Main tasks
  - Defining international units
  - Realization of the measurement units by scientific methods
  - Realization of traceability process and documentation of uncertainties

METROLOGY (2)

- Legislative frame of the Metrological System of the Czech Republic: Act No. 119/2000 Coll. + about 12 amendments
- Measuring instruments serve to determine the value of a measured physical quantity; along with supplementary measuring devices are divided to:

  a) standards;

  b) legally controlled measuring instruments

  c) working measuring instruments

  d) certified reference materials

METROLOGY (3)

- Standard is an object, system or experiment that bears a defined relationship to a unit of measurement of a physical quantity; fundamental reference for a system of weights and measures against which all other measuring devices are compared; 3 levels – primary, secondary, 3rd level standards (working standard)
- Legally controlled instruments should guarantee correct measurement results
  - under working conditions
  - throughout the whole period of use
  - within given permissible errors
- Working measuring instruments are neither standards, nor legally controlled
- Legally controlled measuring instruments are in the Czech Republic approved by the Decree of the Office for Standardization, Metrology and Testing (OSMT) valid since od 1.1. 2000,

METROLOGICAL ASPECTS of GNSS (1)

- In accordance with the Act No 119/2000 Coll. And the Decree of OSMT the GNSS receivers are working measuring instruments
- For these instruments the Act prescribes in Article 5 Traceability, § (1) and (6):

(1) *For purposes of this Act, the traceability of measuring instruments means incorporation of given measuring instrument into an uninterrupted sequence of transfer of the value of quantity beginning with the standard of highest metrological quality for the given purpose.The traceability of working measuring instruments shall be determined by the user of the measuring instrument.*

(6) *The traceability of working measuring instruments in use may be established by their users themselves by means of standards calibrated by the Czech Metrology Institute or a calibration service centre or with assistance of other users of measuring instruments who have appropriate main standards traceable to standards of the CMI*

METROLOGICAL ASPECTS of GNSS (2)

- GNSS positioning is based on very precise caesium and rubidium frequency standards on board navigation satellites and controlled by the ground control segment
- Accuracy of these standards is equivalent to the accuracy of national frequency standards; they are permanently available and used by GNSS receivers providing them the length and time unit and, thus, the scale of the measured terrestrial network
- Calibration of GNSS receivers against the national frequency standards is groundless and practically unfeasible
- Therefore, for the GNSS „measuring instruments" is, according to Article 11, § (5) of the Act, *another way or method* more suitable to ensure the uniformity and accuracy of the instrument to the necessary extent by the user
- Such a method can be a verification of the whole measuring system, inc. SW and observation method in a standard way with linking to a standard of 3D position represented by a test and calibration baseline

VERIFICATION of GNSS INSTRUMENTS (1)

Laboratory

- Special equipment and metrological staff
- Verification of navigation (aviatic, navy) systems, military purposes
- Simulation of GNSS signals and conditions of receiving and processing signals
- Required lower accuracy level than in geodesy
- Accuracy and uncertainty characteristics of instruments under different conditions and statistical evaluation of the system integrity, i.e. probability of errorneous results and/or system failure

VERIFICATION of GNSS INSTRUMENTS (2)

Verification by Measurement

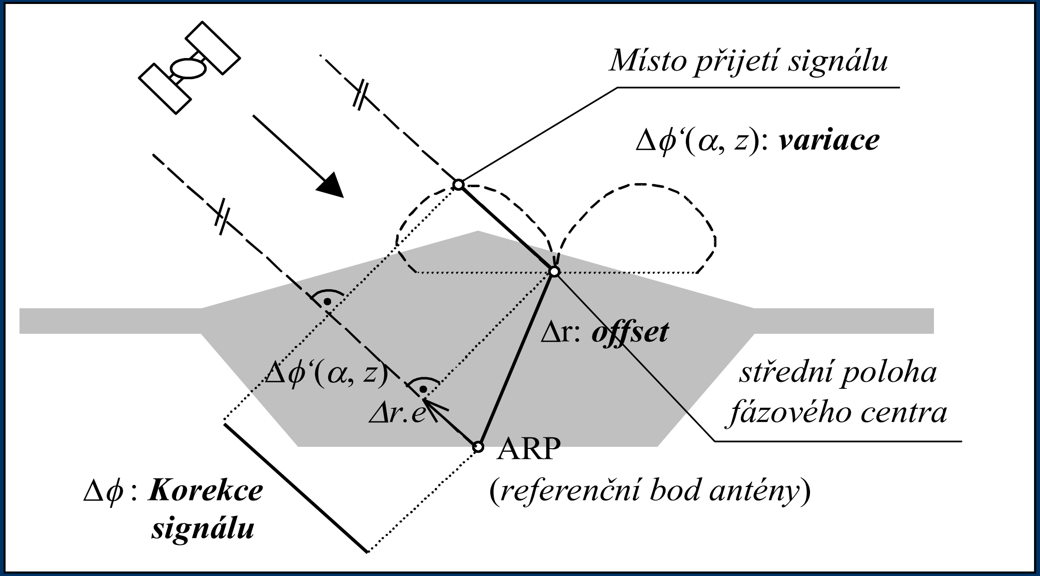
- Observation of GNSS satellites under known conditions
- Observation at well monumented markers with forced centering using theoretically substantiated observation programme
- Comparison of receivers (reference and tested) – „zero baseline" method when more than one receiver receives signals from the same antenna
- Antenna calibration or comparison – individual effects of the used receivers should be eliminated; using receivers of the same type which work with the same precise reference frequency standard
- Antennas are <u>the only component</u> of the GNSS measuring systems which can really be calibrated in the sense of metrology, i.e. it is possible to determine parameters/corrections to the actual PC position

VERIFICATION of GNSS INSTRUMENTS (3)

Antenna Calibrations

- Necessary in all positioning applications at the millimetre accuracy level (geodynamics, deformation monitoring)
- Determination of an „offset", i.e. vector of the line connecting the ARP (geometric or physical antenna centre) and the phase (or „electronic") antenna centre as an input of received signals
- Determination of PC

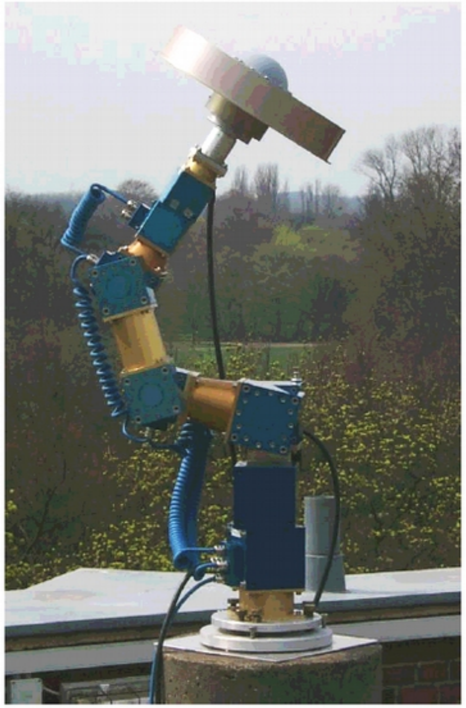
  variations



VERIFICATION of GNSS INSTRUMENTS (4)

“Field” antenna calibration

- Based on real GNSS signals
- Determination of horizontal components of PC by measurement with rotated and tilted antennas
- PC positions providing the best approximation of coordinate differences or lengths of vectors between the values determined with different antenna positions and orientations and „correct“ values (determination by a coupl of reference receivers and antennas)



(original AOAD/M_T Choke Ring antenna on the robot during calibration procedure)

VERIFICATION of GNSS INSTRUMENTS (5)

Testing Software

- SWs provided by GNSS HW manufacturers work well
- Testing by formal checking inputs, outputs, general options, variability of parameters, solution of ambiguities, tropospheric and ionospheric corrections, PCV corrections
- Evaluation of formats and contents of output files provides an information on SW quality concerning its flexibility, adaptability to further link-up SW for processing GNSS results but also information for checking correctness of processing or observation methodology
- Defining a „reference software", wrt which the results of processing of tested systems are related

VERIFICATION of GNSS INSTRUMENTS (6)

GNSS TEST BASIS – a CONCEPT (1)

- GNSS TB should be a standard for calibration and testing GNSS receivers and antennas;
- Testing GNSS measuring systems comprises verification of the receiver functionality, methodology of observations and data processing; the result is a certificate giving an evidence of a proper function of the tested measuring system (receiver, antenna, SW and methodology of their use) with respect to the given criteria
- Calibration of GNSS measuring instruments means determination of numerical values of parameters related to the instruments (usually PC variations)
- GNSS TB is realized as a network consisting of well monumented geodetic markers with ETRS89 coordinates determined with a high accuracy

VERIFICATION of GNSS INSTRUMENTS (7)

GNSS TEST BASIS – a CONCEPT (2)

- Reference ETRS89 coordinates are determined with the help of the most precise GNSS receivers and individually calibrated antennas; the observations are processed by scientific SW package using precise orbits

- Coordinate differences between individual points of the baseline are verified by very precise terrestrial geodetic methods (EDM, very precise levelling) using the certified (calibrated) measuring equipment

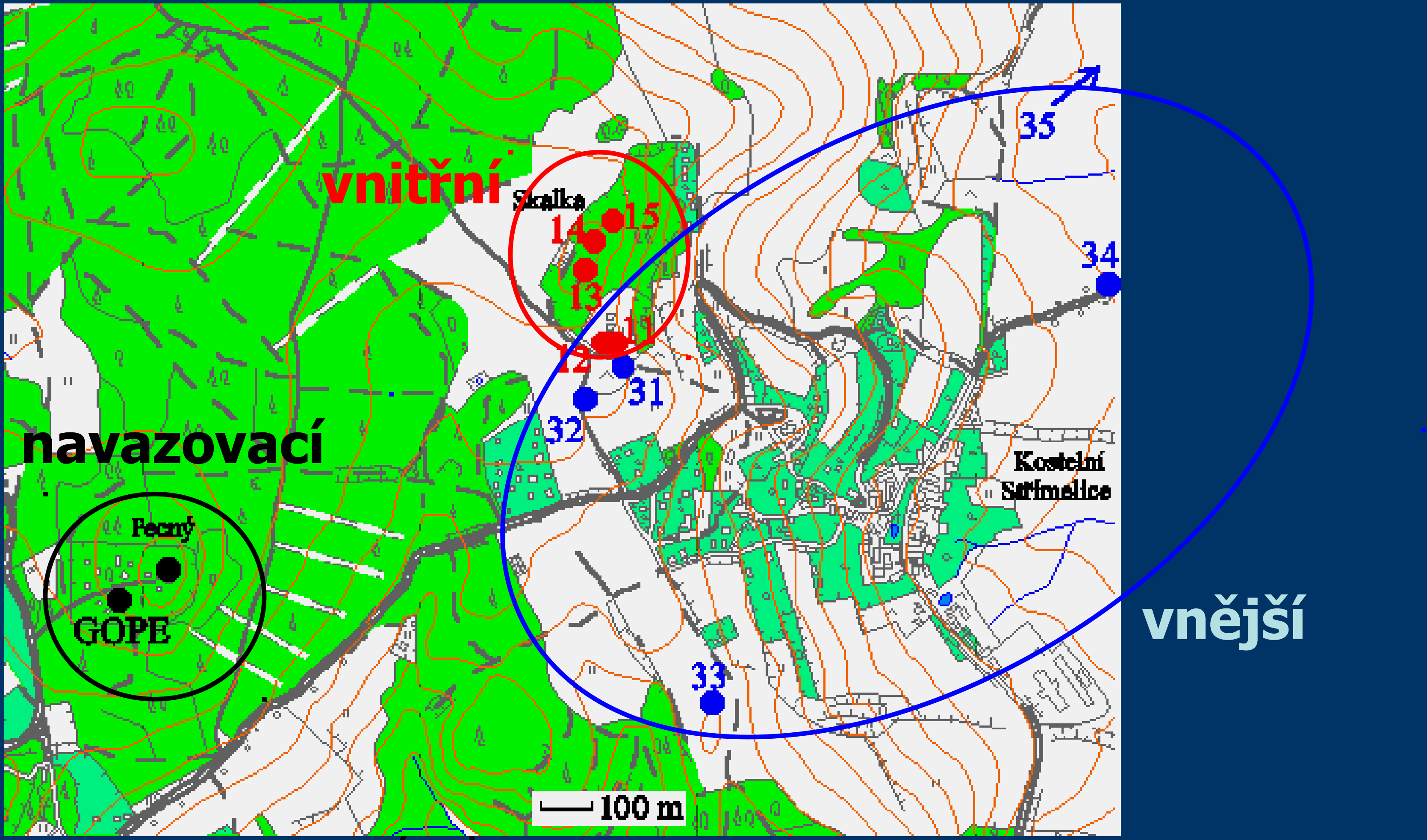
- Reference coordinates are evolving – they are periodically checked (updated) by repeated observations and their evolution in dependence on the observation epoch is monitored

GNSS TEST BASIS SKALKA – GO PECNY

- Built-up in 1999/2000 in the area of Geodetic Observatory Skalka (dependency of the GO Pecny) and its surroundings
- Destined for verification of GNSS measuring instruments by comparing the results achieved by the tested instruments with the reference quantities
- Inner basis is destined for most precise testing and calibrations
- Outer basis consists of 5 monumented markers distributed up to 10 km distance from the inner basis to enable testing the instruments, methodology and SW in the conditions usual in the surveying practice
- Link to the IGS/EPN/CZEPOS station Pecný (GOPE) located at the Geodetic Observatory Pecný (1 km from the inner basis) to enable a link to the ETRS89 official realization

GNSS TEST BASIS SKALKA

Distribution of geodetic test markers



GNSS TEST BASIS SKALKA

Inner basis - monumentation

- Located at the GO Skalka
- Pillars with forced centering
- Concrete pillars protected by a concrete mantle to mitigate temperature variations and sunshine)

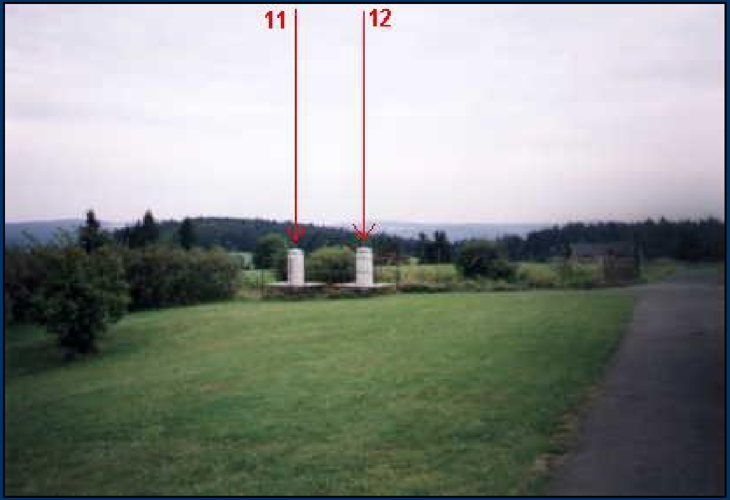
Inner basis (2)
calibration pillars

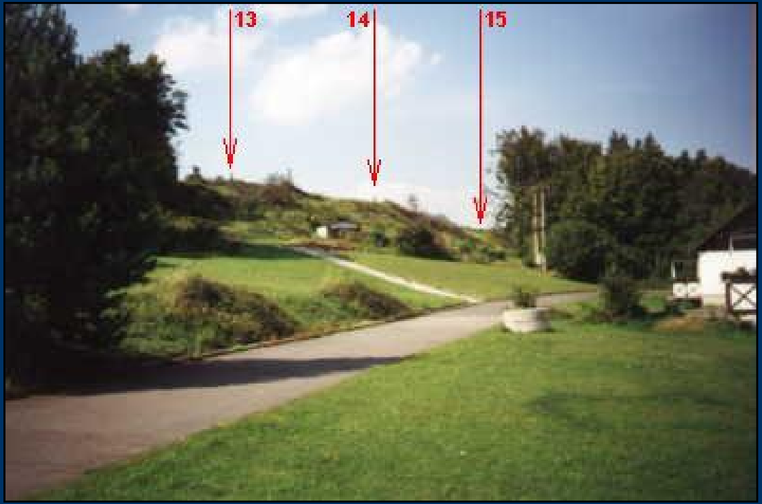
- Two pillars located at a distance of 3.5 m from each other to enable eventual calibration of antenna PC

GNSS TEST BASIS SKALKA

Inner basis (3)

- Distance between pillars ranging from 50 to 100 m





GNSS TEST BASIS SKALKA

Outer basis

- Monumented by granit prism with a brass marker on the top which indicates position of the point
- Protection against damage
- Points distributed at different distances and height differences with respect to the inner basis
  - 50 m, 150 m, 500 m, 1 km, a 11 km
  - Height difference up to 300 m

LINK to the IGS/EPN/CZEPOS STATION PECNÝ

- Link to the official realization of the ETRS89
  - EPN/IGS/CZEPOS station GOPE
  - Excentric sites of M-GEX and MGM projects
  - Excentric site (original EUREF CS-H-91) on the top of triangulation tower not more in use

DETERMINATION of REFERENCE COORDINATES

(1)

- Inner basis observed by GNSS in the years 2000, 2005, 2007, 2008, in 2008 a control measurement carried out by the external subject (TU Brno); in 2011 observed two outer sites close to the inner basis
- Link to the IGS/EPN station GOPE only by GNSS
- Antennas calibrated in Geo++
- Control measurements by very precise classical terrestrial methods in 2000, 2005 (CTU Prague), 2006 (University of Bundeswehr, Germany), 2007, 2008 (Accredited Metrological Laboratory, RIGTC), 2012 (TU Ostrava) using calibrated instruments (EDM, digital levelling)
- Duration of measurements
  - Inner basis 4 x 24 hrs (i.e. 96 hrs) in each campaign
  - Outer basis 9 – 24 hrs in each campaign
- Processing of observations by Bernese SW
- Transformation of coordinates into the conventional user system S-JTSK

(2)

Comparison of Terrestrial and GNSS Observations

- Comparison of results of terrestrial measurements from individual campaigns and their comparison with GNSS
- Differences of terrestrial measurements between campaigns within the limits of 2 mm (both horizontal positions and heights
- Standard differences between the results of terrestrial and GPS campaigns on the level of 3 mm (horizontal positions and heights)
- In isolated cases the differences between the GNSS results from different years up to 7 mm in position and 9 mm in height
- Differences between directly measured slant lengths and the lengths computed from GNSS-determined coordinates range from 0.1 mm to 0.8 mm

(3)

METROLOGICAL CHARACTERISTICS

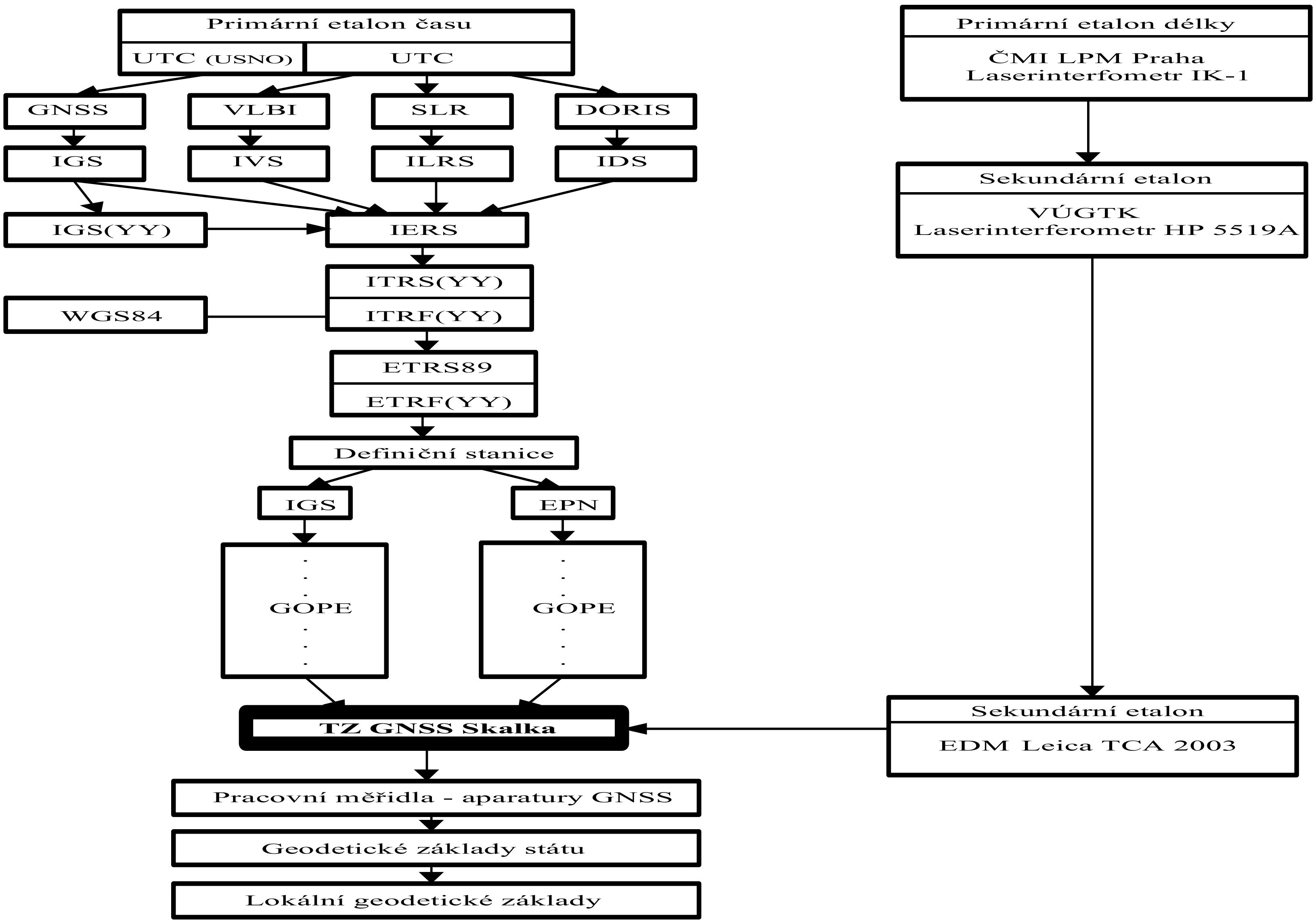
OF THE GNSS TEST BASIS

- Measuring range: 2 m – 10 000 m
- Repeatability: $1,25 \times 10^{-3}$ m for horizontal components

  $4,10 \times 10^{-3}$ m for vertical component
- Uncertainty : 3×10^{-3} v X,Y,Z for points of inner basis

  6×10^{-3} v X,Y,Z for points of outer basis

TRACEABILITY SCHEME of the TB GNSS



GNSS TB – REFERENCE STANDARD of 3D POSITION DECREE No ECR-110-14 by CMI, 2009

ČESKÝ METROLOGICKÝ INSTITUT
ÚSEK GENERÁLNÍHO ŘEDITELE
Okružní 31, 638 00 Brno

SCHVALOVACÍ PROTOKOL REFERENČNÍHO ETALONU PROSTOROVÉ POLOHY ČR

č. ECR 110-14

Datum vystavení: 21.5.2009

RNDr. Jiří Tesař, PhD.
odborný ředitel pro FM

Český metrologický institut -2-

Název etalonu:	Etalon prostorové polohy
Subjekt pověřený uchováváním etalonu:	VÚGTK, v.v.i. Ústecká 98 250 66 Zdiby
Sestava etalonu:	Je uvedena v dokumentaci k etalonu.
Základní metrologické charakteristiky:	Jsou uvedeny v dokumentaci k etalonu.
Místo a čas vyhotovení:	VÚGTK, v.v.i., (základna Skalka) etalon budovánt v letech 1999 až 2008
Zvláštní podmínky uchovávání:	Podmínky uchovávání jsou uvedeny v dokumentaci k etalonu.
Datum oponentního řízení:	Závěrečná oponentura úkolu PRM 2008.
Garant etalonu:	Ing. Jaroslav Šimek

V souladu se zásadami ČMI č. 011-ZS-C011 se **s c h v a l u j e a v y h l a š u j e** předmětný etalon **referenčním etalonem ČR**

RNDr. Jiří Tesař, PhD.
odborný ředitel pro fundamentální metrologii ČMI

USE of GNSS TB – CALIBRATION PROCESS

1. Differences between measured and reference coordinates
2. Conversion of differences to N,E,UP components
3. Identification of maximal values in each N,E,UP component
4. Computing STDs of unit weight for each component
5. Computation of horizontal coordinate rms error
6. Computation of standard uncertainties of rms errors
7. Computation of extended uncertainties
8. Comparison of STDs resulting from the calibration with the STDs for the method used for calibration

USE of GNSS TB – CALIBRATIONS 2009 - 2013

Method	N/S (mm)	E/W (mm)	UP (mm)	Number of differences
all	6.1	5.3	13.0	2026
Fast st.	4.3	3.7	11.2	612
RTK all	6.7	5.9	13.7	1414
RTK	7.6	7.4	14.7	541
VRS	5.8	4.5	13.1	703
FKP	8.0	6.1	13.6	108
PRS	4.9	3.1	11.6	62

CONCLUDING REMARKS

- GNSS Test Basis was built-up in the years 2000 – 2008 at the RIGTC – Geodetic Observatory Pecný/Skalka
- In May 2009 it was declared National Reference Standard og 3D Position for the Czech Republic by the Decree ECR-110-14 issued by the Czech Metrology Institute
- In 2009 it was included in the Regulatiopns on Metrology of the Czech Office of Surveying, Mapping and Cadastre (NMCA) as one of the higher order standards obligarory within the responsibility of the COSMC
- GNSS TB is regularly maintained by periodic re-measurement by GNSS and terrestrial methods – the upcoming one will take place in June/July 2014
- Number of calibrations has been increasing after the COSMC Regulations on Metrologyl had come into force in 2009; the Regulations prescribe for GNSS insrtruments the re-calibration period of 3 years