Academic Training
Geodetic Metrology for future accelerators

Geodetic Infrastructure for New Accelerator Projects

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Outline

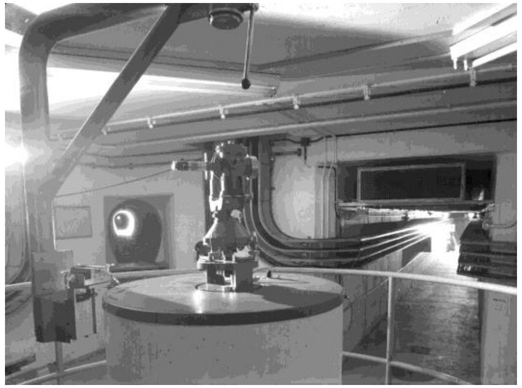
- Definition
- Evolution of the geodetic infrastructure of CERN accelerators
- The Future Circular Collider (FCC)
- Concepts for a new geodetic infrastructure
- Geoid model
- Link with neighbouring geodetic systems
- Ongoing developments

Geodetic infrastructure: definition

The geodetic infrastructure for accelerator regroups:

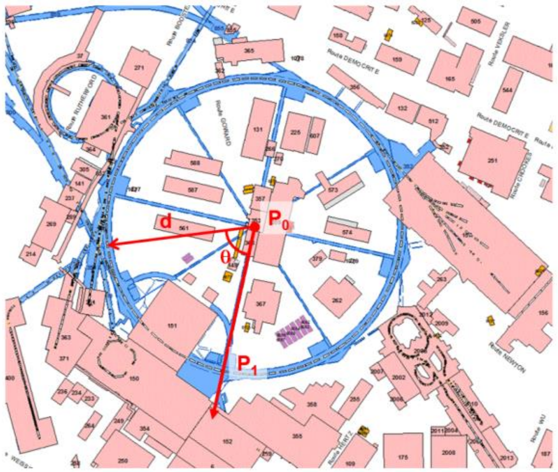
- The coordinate system (set of rules for assigning coordinates to point)
- The geodetic datum (set of parameters that describe the position, the scale and the orientation of the coordinate system relative to the Earth)
- The vertical datum (set of parameters that describe the relation of gravity-related heights to the Earth) including the geoid model
- Reference frames: realization of the datums through a set of concrete numerical values
- The surface and underground geodetic and levelling networks
- Control and calibration facilities
- Specific software and tools
- Documentation

Evolution of geodetic infrastructure of CERN accelerators

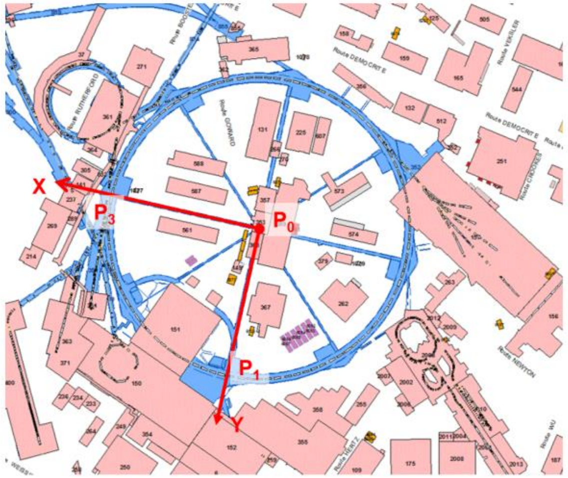


1955-1969: the Earth is flat around the Proton Synchrotron

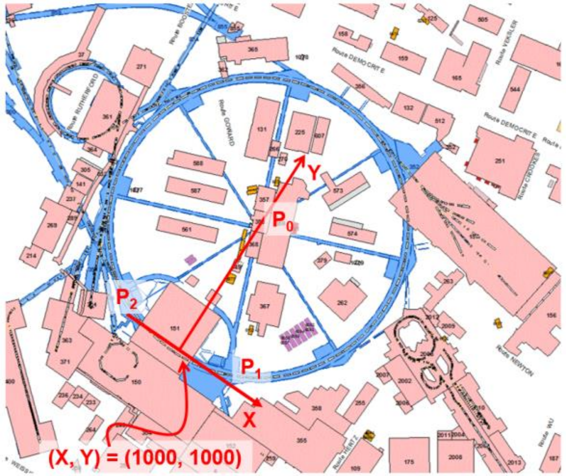
- **CCS: CERN Coordinate System**



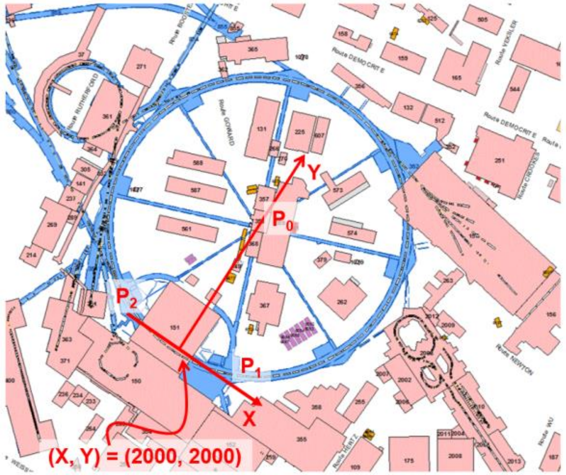
1955: the CSS is a 2D polar system in the plane of the PS, origin at principal point P_0



1959: Rectangular system, origin at principal point P_0



1962: New Rectangular system, X axis oriented from P2 to P1. Y axis is the perpendicular passing through P_0. Origin not at P_0.



1966: Change of the coordinates of the origin to avoid negative values around the PS.

Evolution of geodetic infrastructure of CERN accelerators

1970: Spherical Earth is introduced for the Super Proton Synchrotron

- **Mean Earth Radius: R=6371 km**
- **Altitude P_0=433.660-0.00079=433.65921 m**

  (433.660: Altitude of the PS ring; 0.00079: h_0)

- **Z_{P0}=Altitude P_0 + Cste = 433.65921 + 2000.00079 = 2433.660 m**
- **Effect of sphericity: d²/2R**
  - Effect of sphericity of the Earth is 0.79 mm for the ps (radius d=100 m)
  - Maximum effect: 3.357 m (Maximum distance from P_0 d=6540 m).

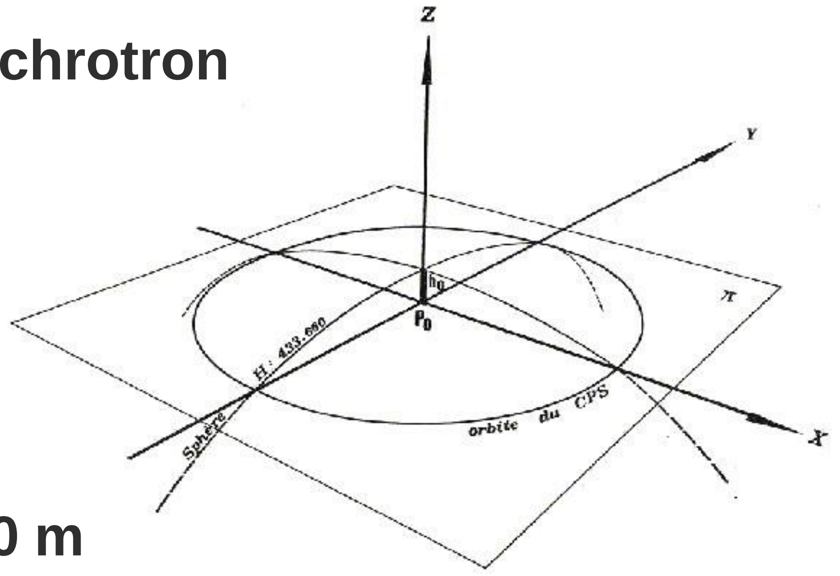
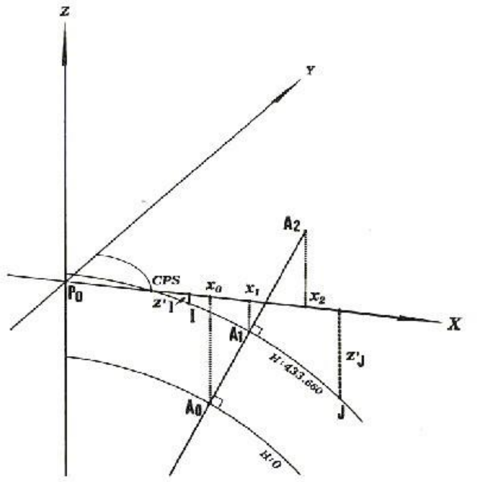


Figure 2

Evolution of geodetic infrastructure of CERN accelerators

1970: Spherical Earth is introduced for the Super Proton Synchrotron

- **Need to continue to work with 3D cartesian coordinates**
- **Orthographic projection**
- **Relatively simple mathematic formulas to reduce observations and compute coordinates into the CCS**



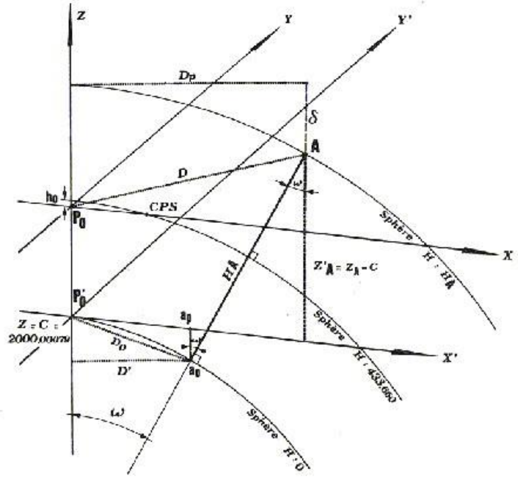
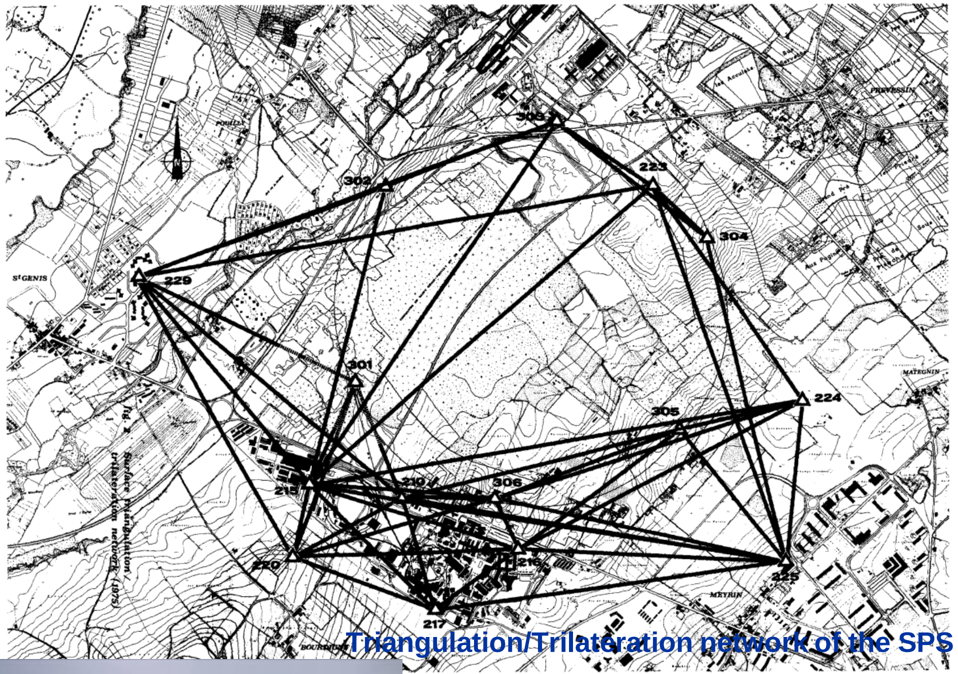


Figure 4

Evolution of geodetic infrastructure of CERN accelerators

1970: Extension of the surface geodetic network

- **Triangulation (angle measurement with a Wild T3 Theodolite)**
  - Precision: +/- 0.5“ (2 mm at 1000 m)
- **Trilateration (distance measurement with a MA 100 Tellurometer).**
  - Precision: 0.5 mm + 1.1 ppm (mm per km)
- **Estimated precision of coordinates (final least square adjustment) better than 1.3 mm**


Triangulation/Trilateration network of the SPS


Distance measurement with a MA 100 tellurometer


dehilster.info

Evolution of geodetic infrastructure of CERN accelerators

1970: Coordinates transfer from surface to the tunnel

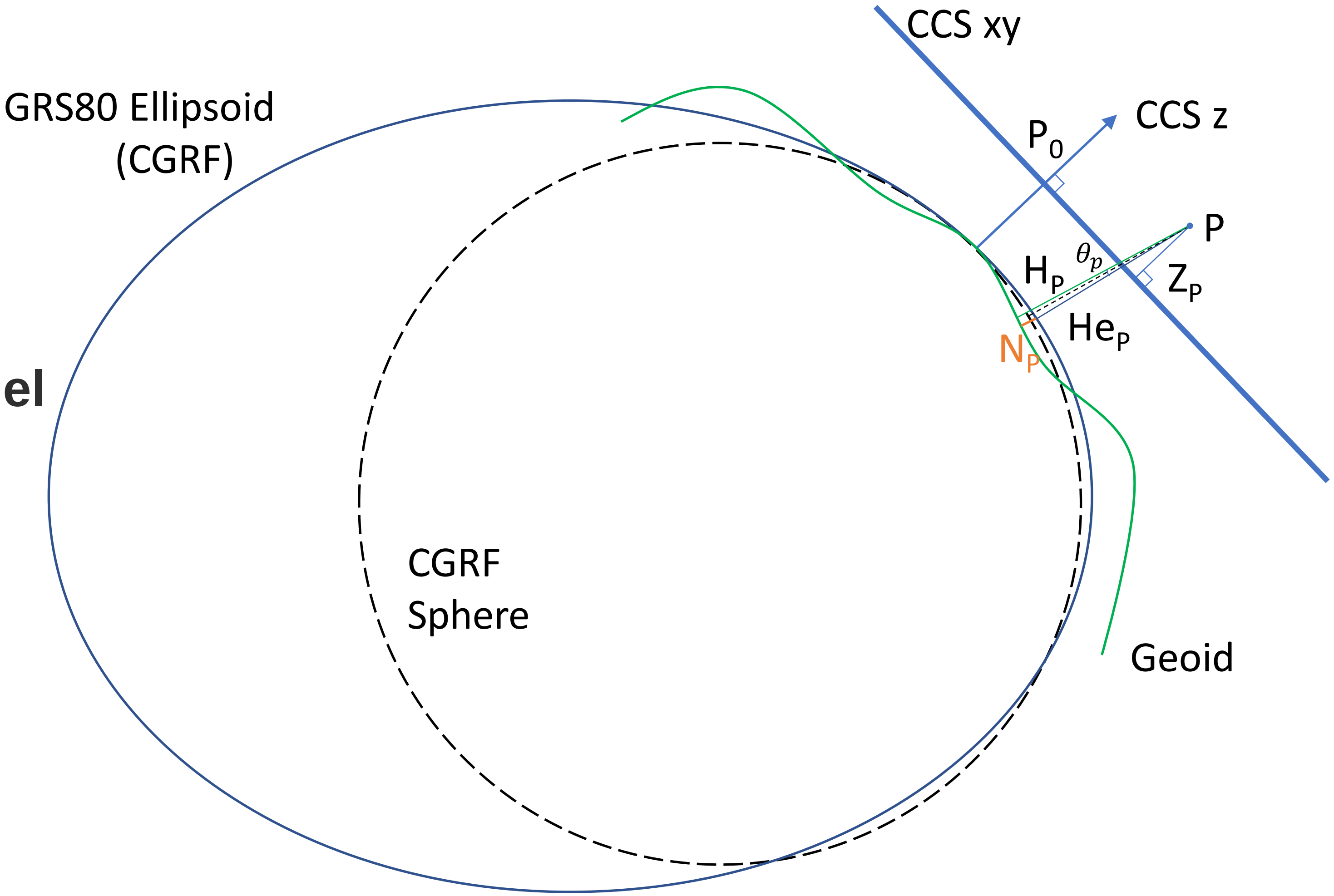
- **Depth of the shaft: between 23 and 62 m**
- **Three different techniques**
  - A plumb-line damped in an oil-bath
  - A nadiro-zenithal telescope
  - A precision nadir plummet Wild GLQ with mercury horizon
- **Accuracy remained within a millimeter**

Nadir plummet Wild GLQ
Guedes, Quintiliano & da silva, Irineu. (2009)

Evolution of geodetic infrastructure of CERN accelerators

1981: LEP

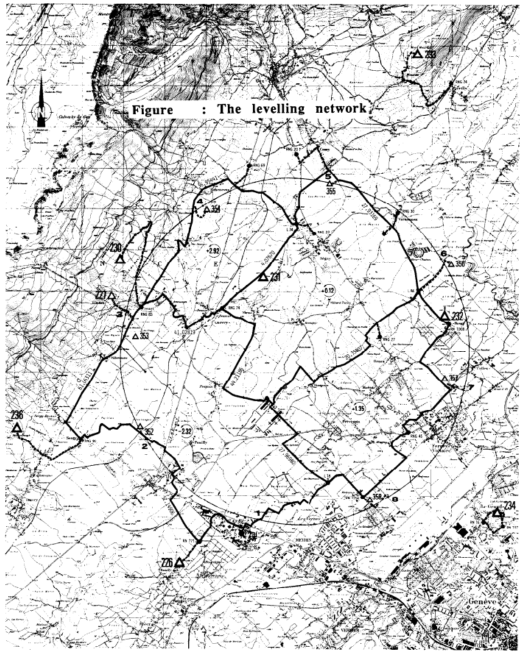
- **Spherical Earth model updated to ellipsoid earth model**
- **Introduction of a gravity field model**
- **For a 140 m pit at the foot of the Jura, deflection of vertical correction is 6 mm**

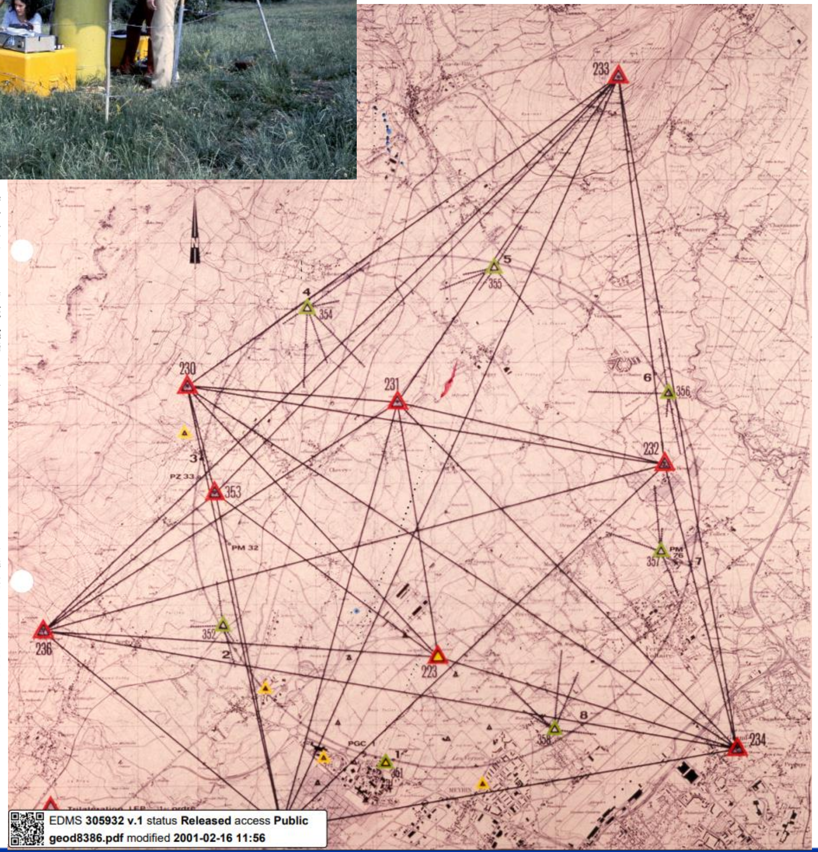


Evolution of geodetic infrastructure of CERN accelerators

1981: LEP

- Extension of the surface geodetic network
- Absolute distances observed with LDM 2 Terrameter (1983, 1985, 1986)
- Reached a millimetric accuracy
- Require intervisibility
- Almost 90 km of levelling route

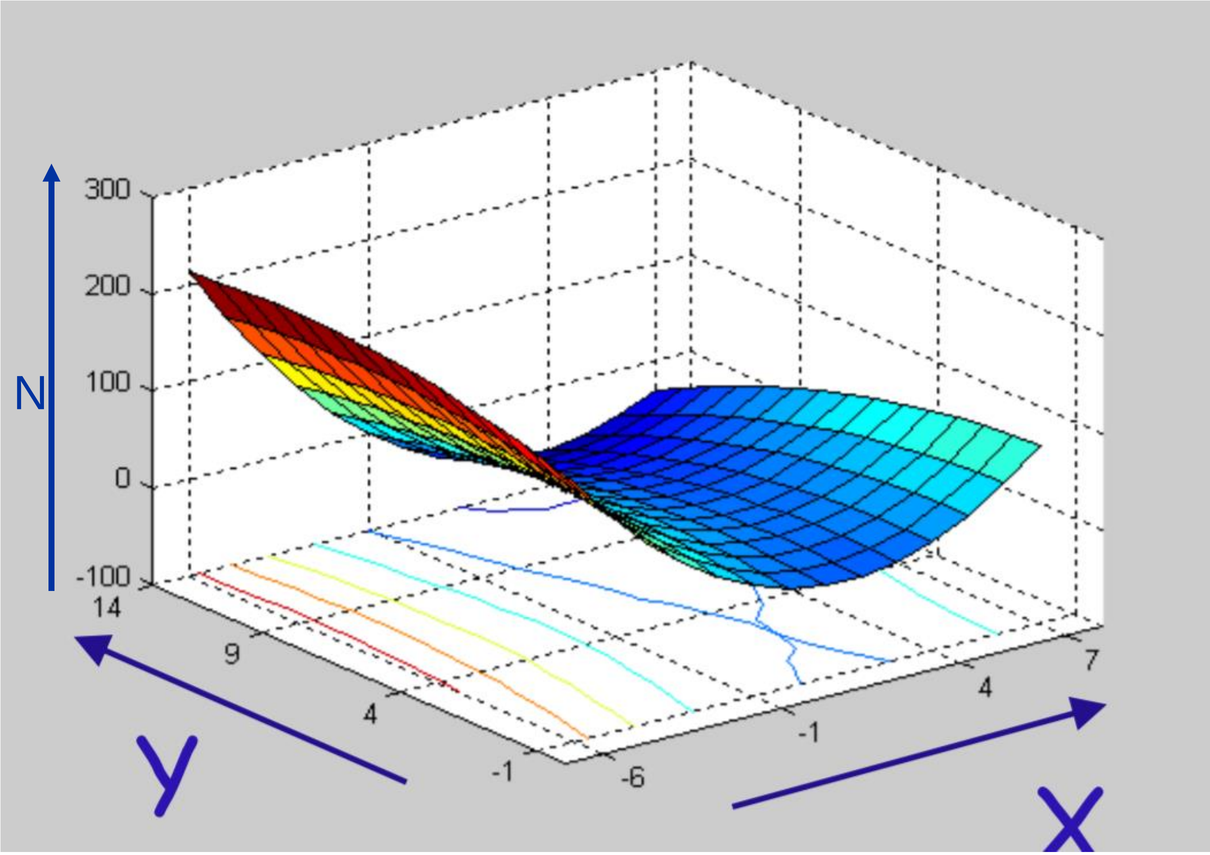




Evolution of geodetic infrastructure of CERN accelerators

1981: LEP

- CG1985 Geoid and pseudo-geoid models
- Hyperboloic paraboloid

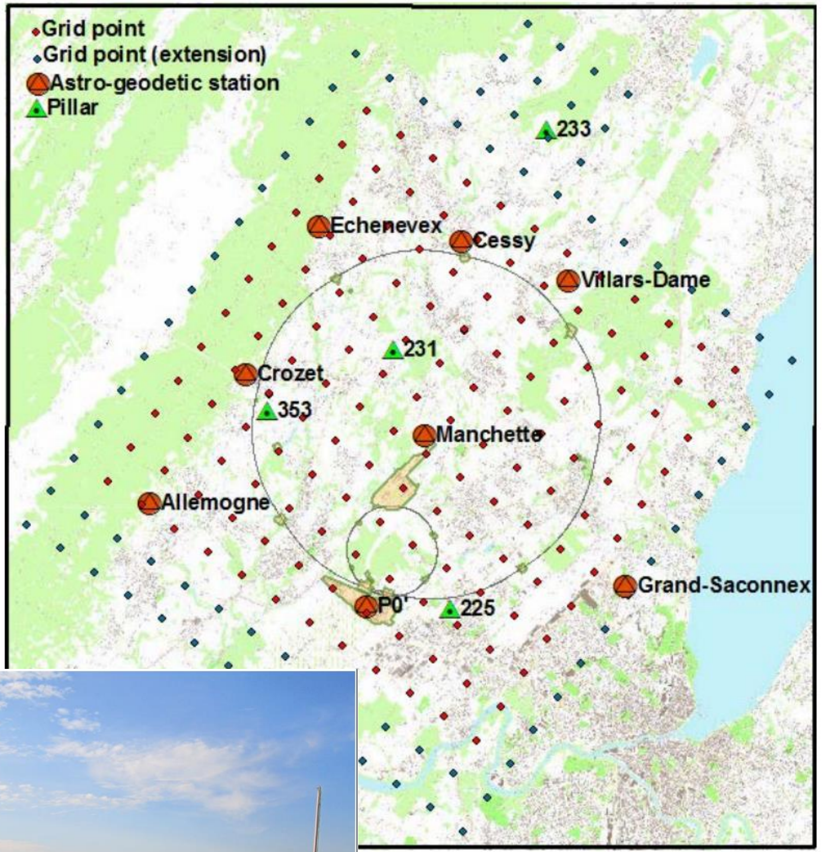


The CG1985 Geoid Model (X, Y in km and N in mm)

Evolution of geodetic infrastructure of CERN accelerators

After the LEP

- 1998: Determination of the surface geodetic network by GPS
- 2000: Update of the geoid model (CNGS project)
- 2017: Determination of the surface geodetic network by GNSS

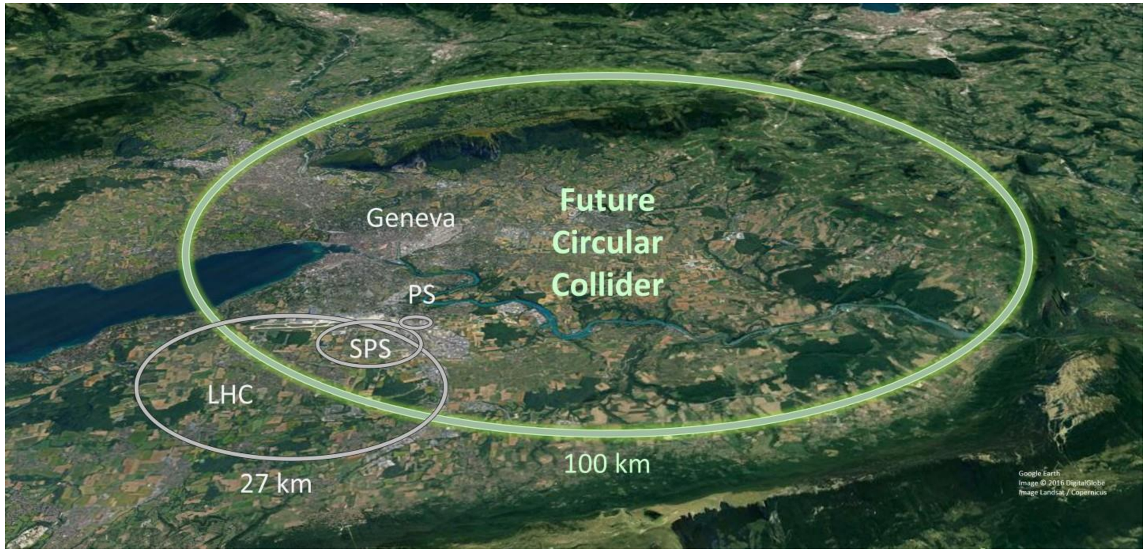


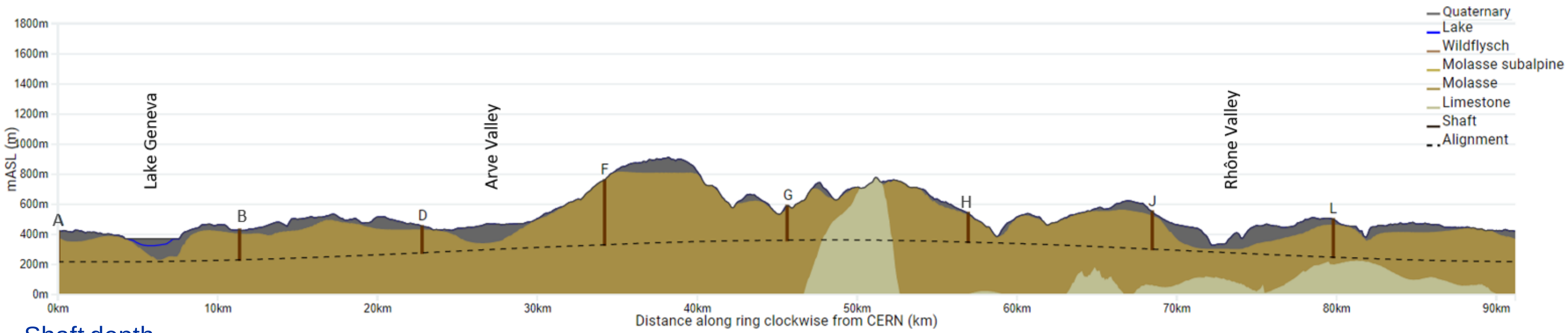
Status of the current CERN geodetic infrastructure

- **The CCS is the reference system at CERN**
- **Adapted for local survey and alignment of the machine within the CERN but not for mapping and civil engineering works**
- **Needs to be updated to be in line with current best geodetic practices**

The Futur Circular Collider

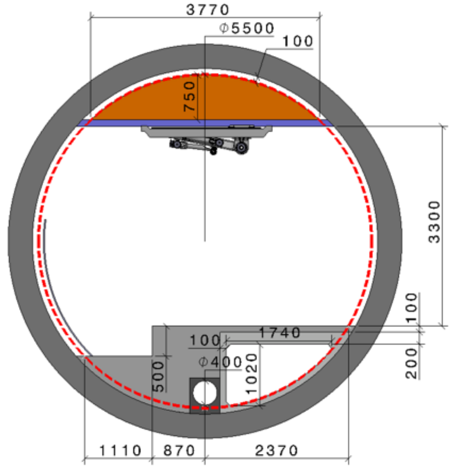
- **91.1 km ring**
- **Extends the geographic area of the CERN facilities from 70 km2 to 1000 km2**
- **8 access shafts**





Shaft depth

A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

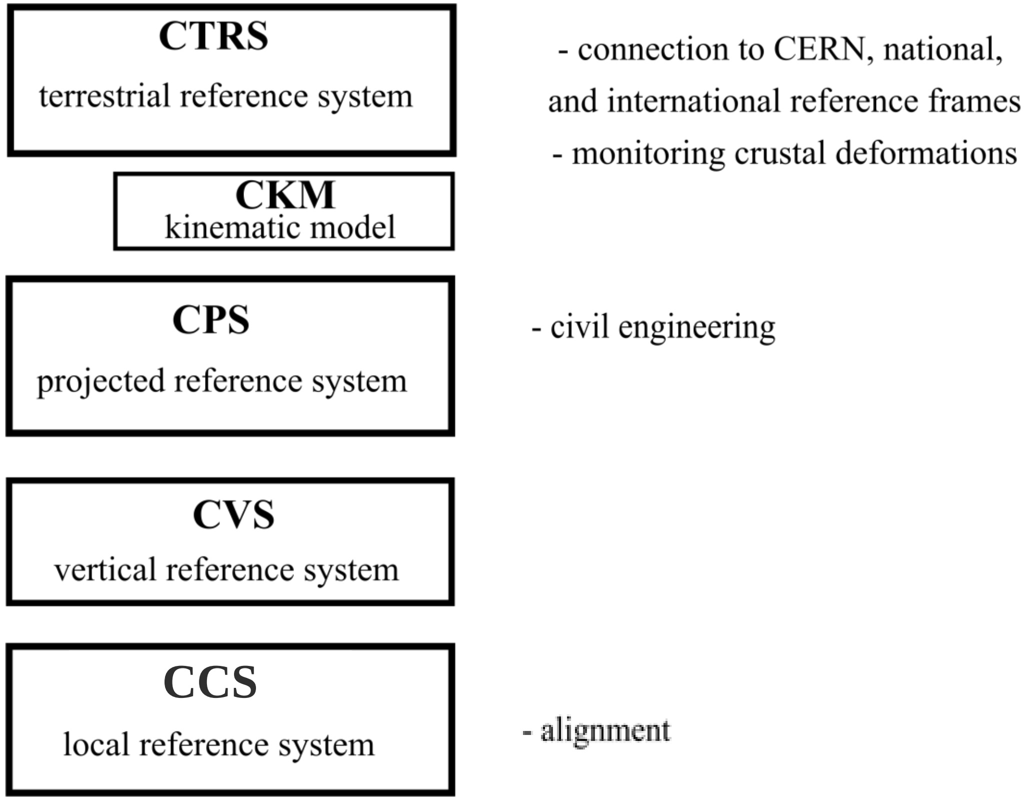


Needs of a new coordinate system

Purposes

- **Civil engineering including tunnelling**
- **Installation and maintenance of infrastructure above/below ground**
- **Monitoring crustal deformations**
- **Connecting facilities to others (locally, nationally, internationally)**
- **Accelerator alignment**

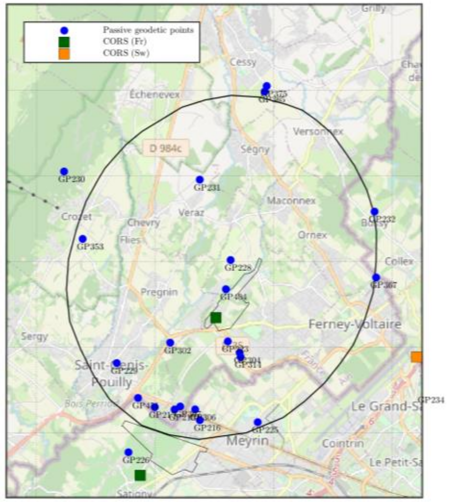
Proposition for new coordinate system

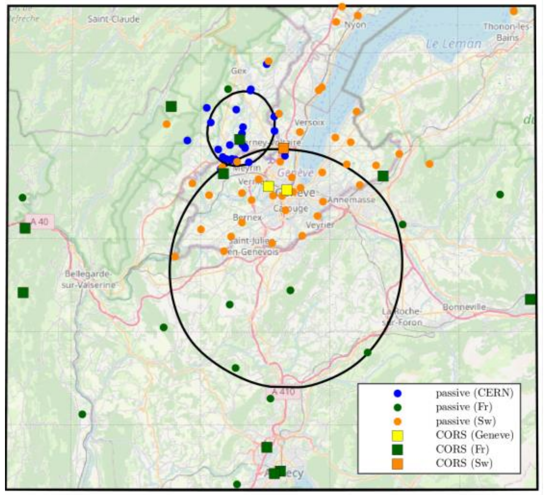


Surface geodetic network

Introduction

- Geodetic networks enable users an access to coordinates
- Consist of physically materialized points with precisely determined coordinates
- Basis: geodetic instruments and techniques (total-stations, GNSS, levels, laser trackers, …)

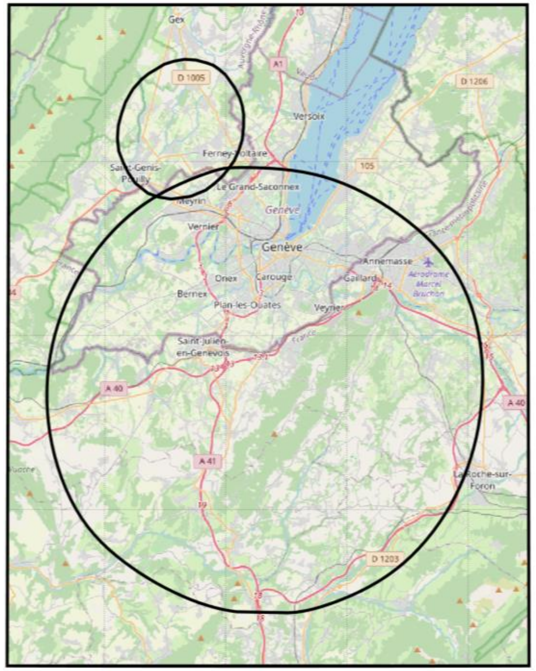




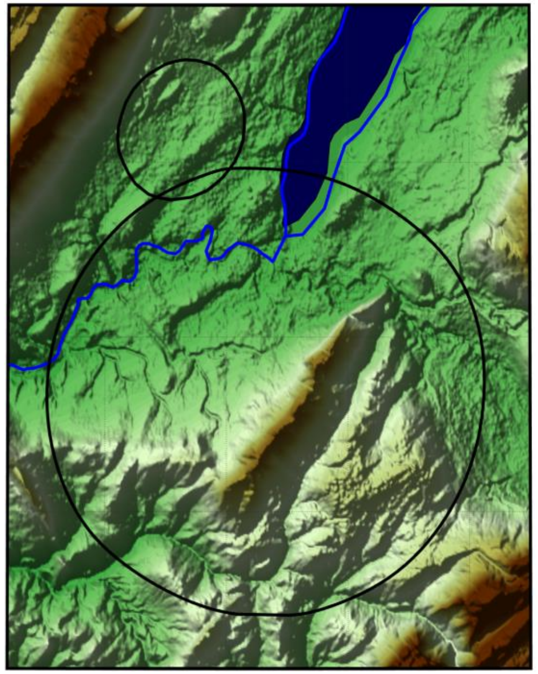
Passive and active geodetic points over the CERN area

Surface geodetic network

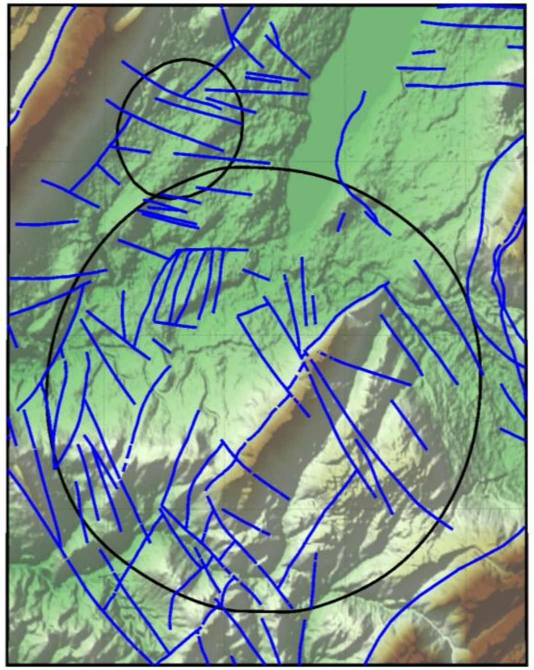
- **Geospatial and geodetic constraints**



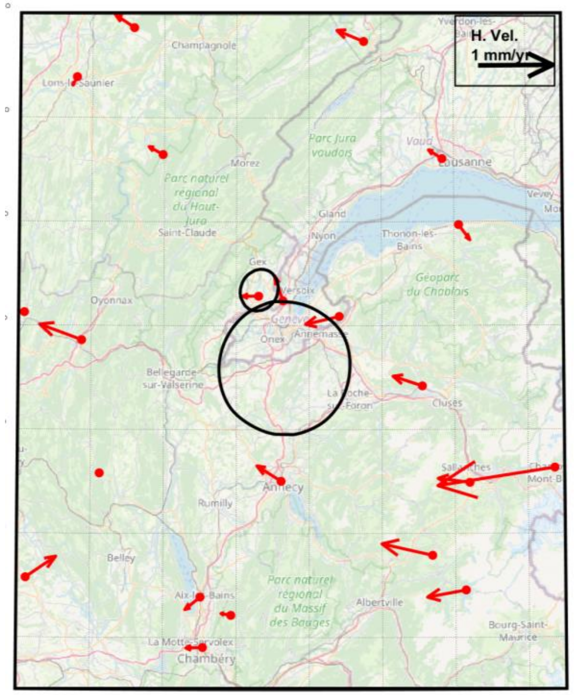
Geographic features (borders, municipalities, roads, ...)



Topographic features (mountains, lakes, rivers, valleys, ...)

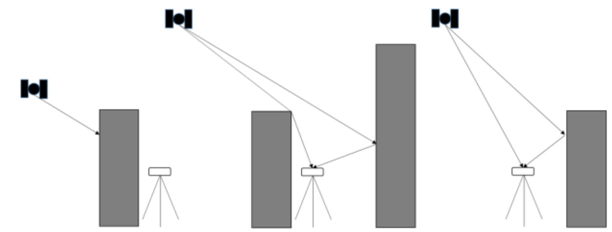


Geological faults



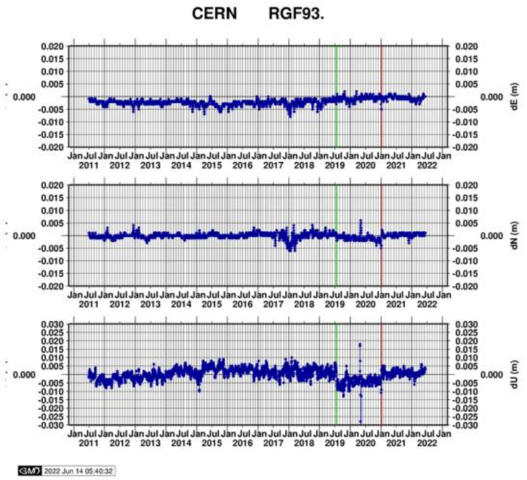
Surface kinematics

Surface geodetic network



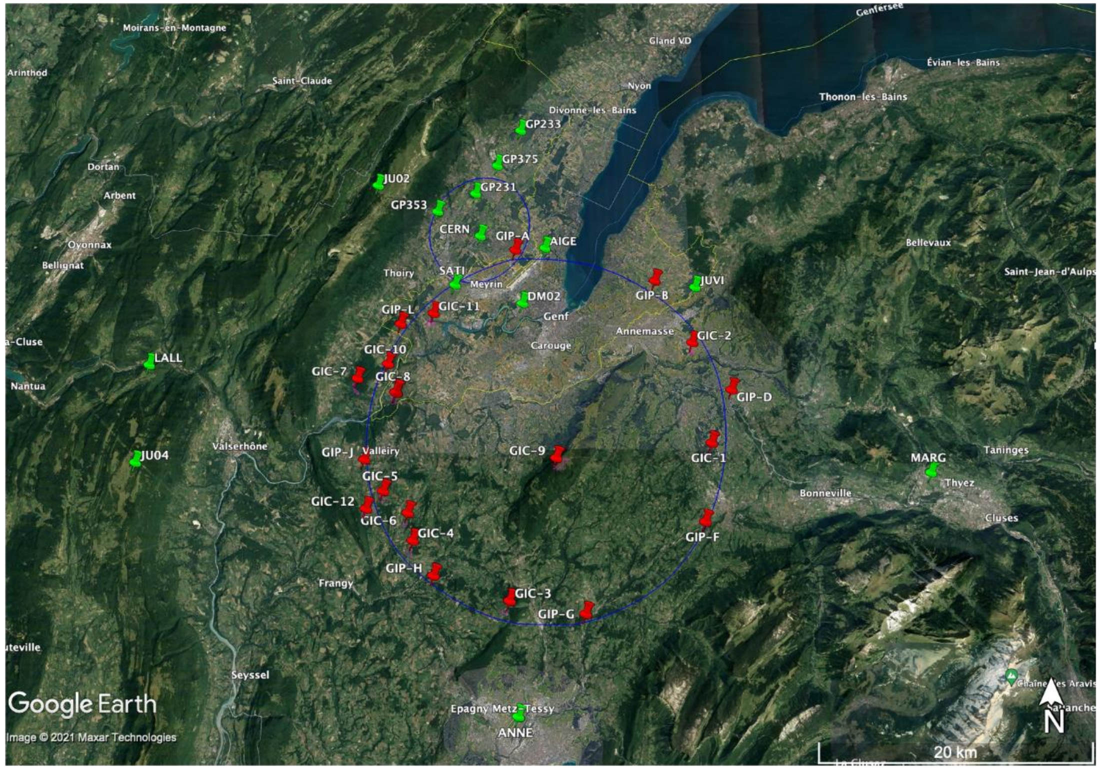
GNSS obstructions and multipath (Kubo et al., 2020)

- **Low level of GNSS obstructions**
- **Low level of multipath**
- **Low level of potential elctromagnetic interference**
- **Underground stable enough for long-term materialization**
- **Accessibility of the site at all times (24/7)**
- **Safety of operators and equipment during use of the point**
- **Land-use agreement with property owner for at least the time until completion of the FCC construction**



Surface geodetic network

- **Conceptual design report for the establishment of a surface geodetic reference network including control baselines**
  - P-SGN (Primary):
    - Realize CTRF
    - Determine CKM
    - Main tunnel network
  - S-SGN (Secondary):
    - Densification
    - Geomonitoring
    - Construction
    - Portal networks
  - V-SGN (Vertical):
    - Realize CVF
    - Geomonitoring
    - Construction



Conceptual proposal of P-SGN comprising points to be newly established (red) and existing points (green).

Acronyms: P-SGN primary SGN, S-SGN secondargy SGN, V-SGN vertical surface geodetic network, GNSS: Global Navigation Satellite System

Surface geodetic network

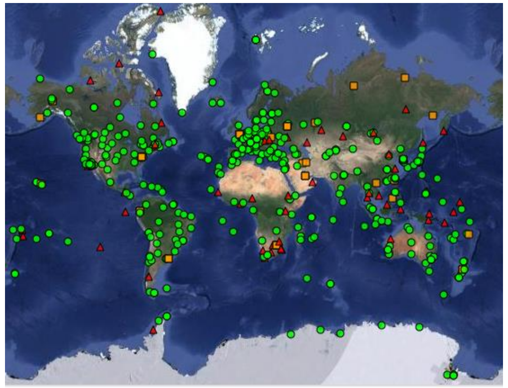
- **Key characteristics of the various types of surface geodetic network (SGN) points**

	P-SGN	S-SGN	V-SGN
Purposes	Realize CTRF Determine CKM Main tunnel network	Densification Geomonitoring Construction Portal networks	Realize CVF Geomonitoring Construction
Coordinates	3D in CTRF 2D in CPF option: 1D in CVF	3D in CTRF 2D in CPF option: 1D in CVF	1D in CVF
Materialization	Pillar, or ground level foundation with precision marker	Various, typically ground level marker	Height bolt
Suitability	GNSS optionally also other surveying equipment	various surveying equipment	geometric levelling
Precision	individually specified all: $\sigma_{N,E} \leq 3.5\,\mathrm{mm}$ $\sigma_U \leq 5.0\,\mathrm{mm}$ in CTRF	individually specified typ.: $\sigma_{N,E} \leq 3.5\,\mathrm{mm}$ $\sigma_U \leq 5.0\,\mathrm{mm}$ in CTRF	individually specified all: $\sigma_{\Delta H} \leq 0.5\,\mathrm{mm/km}^{\frac{1}{2}}$ w.r.t. V-SGN (up to 5 km)
Reliability	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$	AZ≤ 3 for $\alpha_0 = 1\%, \beta = 10\%$

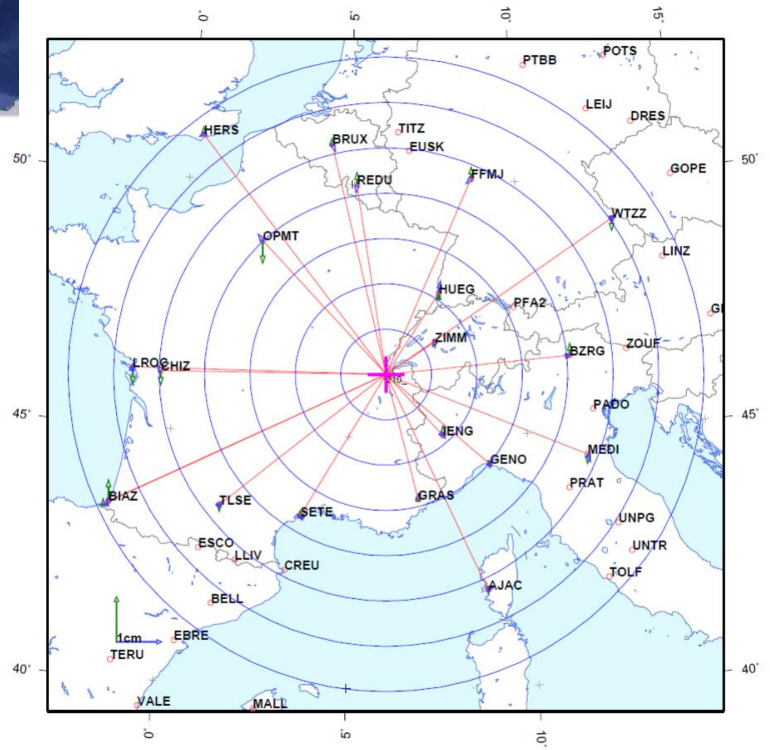
Surface geodetic network

Tying in

- **International Terrestrial Reference Frame**
- **European Terrestrial Reference Frame**
- **Reference GNSS permanent stations**
    - Evenly distributed
    - Reliable availability



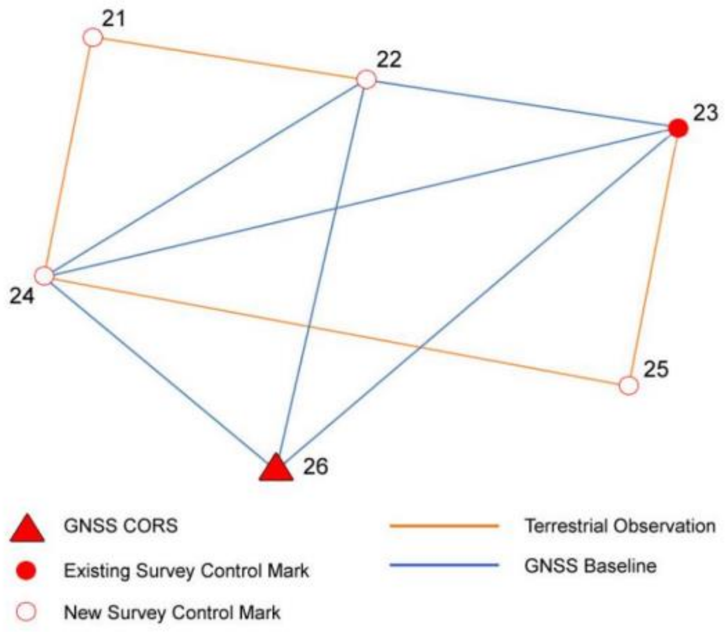
IGS global reference network (igs.org)



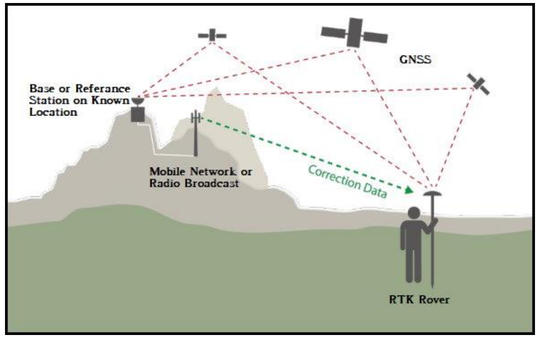
Distribution of reference stations from permanent networks known in ITRF2014 (IGS14) around the CERN

Network densification and survey

- **Combination of GNSS and terrestrial techniques**
- **Surveying and Staking out**
- **Challenges**
  - Keep control on the error propagation
  - Maintain consistency



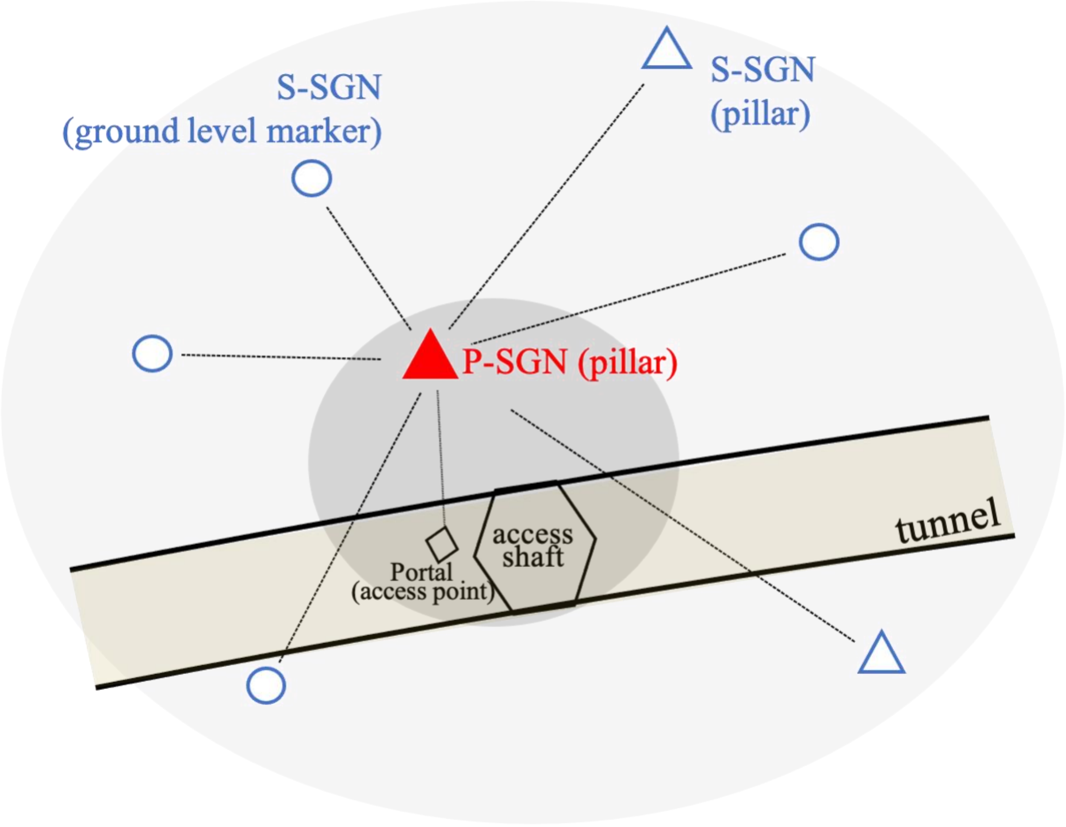
Reference network densification (icsm.gov.au)



Real Time Kinematic

Network densification and survey

- **Tunnel access network**



Schematic layout of a portal surface geodetic network for one tunnel access shaft

Coordinate transfert through shafts

Transfer of 3D-coordinates (north, east, height): plumbing and vertical distance measurements

Optical plumbing

top of the shaft

Nadir plumb instrument

bottom of the shaft

Mechanical plumbing

determination of the wires at the top of the shaft

Mechanical plumb

determination of the wires at the bottom of the shaft

Transmission of direction with gyroscope

Transmission of direction

- Gyroscope
- Control with Inertial Measurement Unit (IMU)

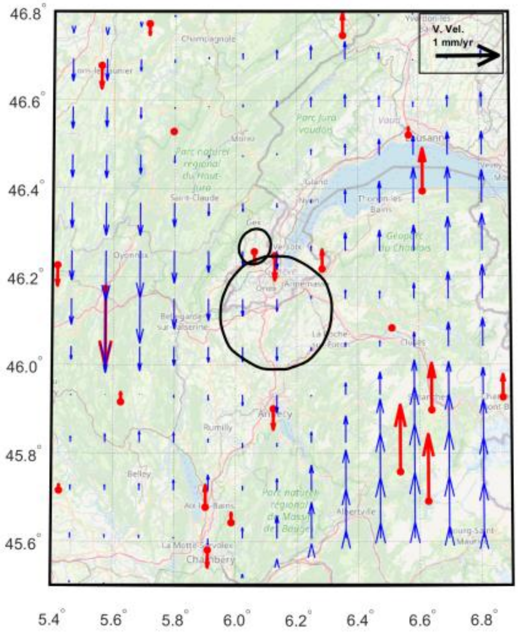
Tunnel reference network

Accurate geodetic traverse

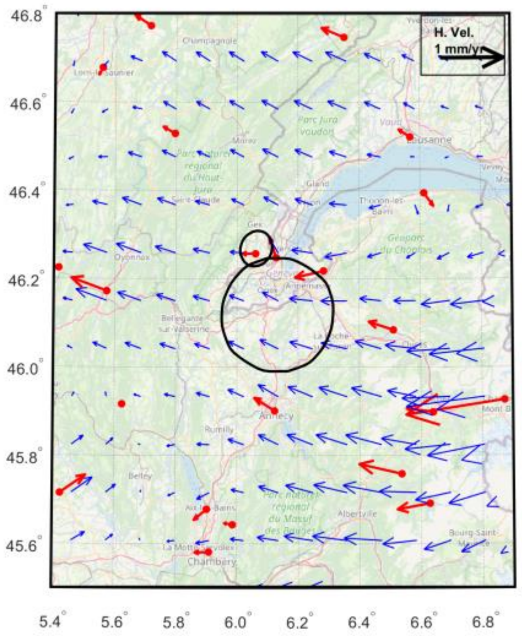
- **Control and monitoring during the construction**
- **Reference for the initial alignement of the machine**

Geokinematics of the FCC area

- **Study of surface and ground motion of the FCC area**
- **Relative surface kinematics are expected to range from 0 to few mm/yr**
- **[EUREF WG project on European Dense Velocities]**



(b) Vertical velocities (v_U).

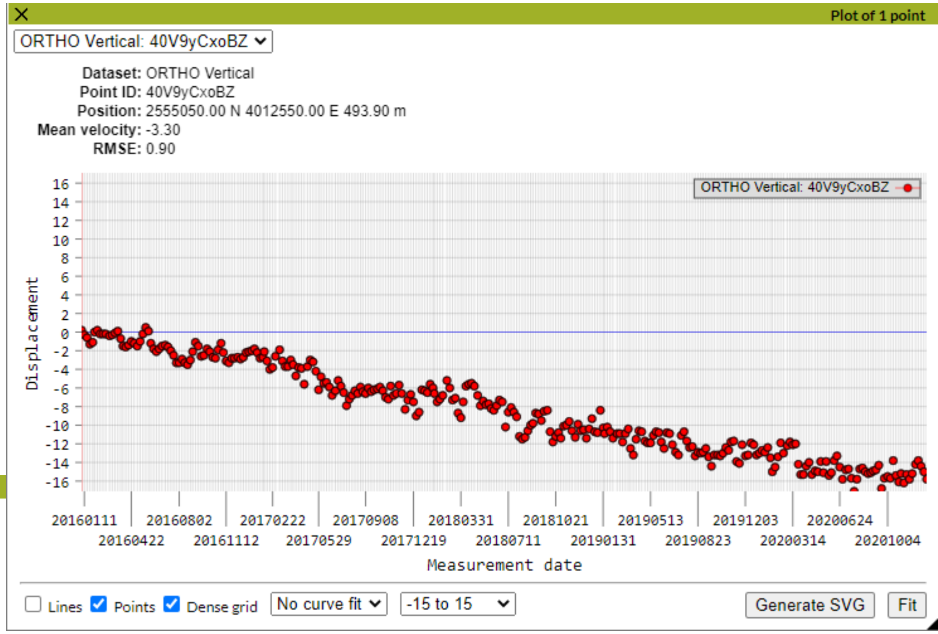


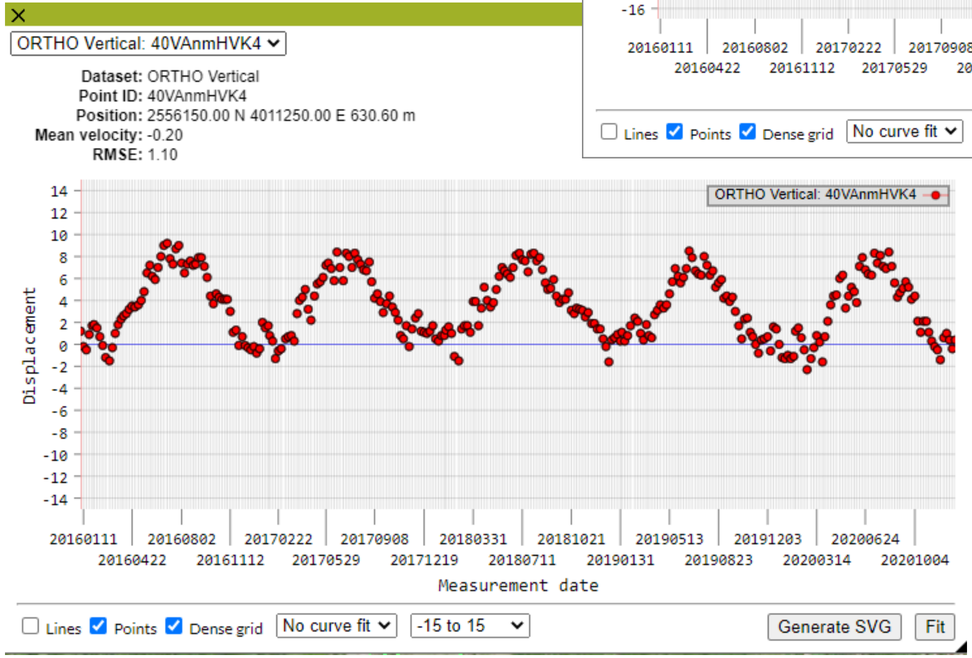
(a) Horizontal velocities (v_N and v_E).

	v_H [mm/yr]	v_U [mm/yr]	σ_H [mm/yr]	σ_U [mm/yr]
CERN	0.2	-0.3	0.2	0.3

Geokinematics of the FCC area

- Global InSAR data
- European Ground Motion Service
- Long trends
- Seasonal effects

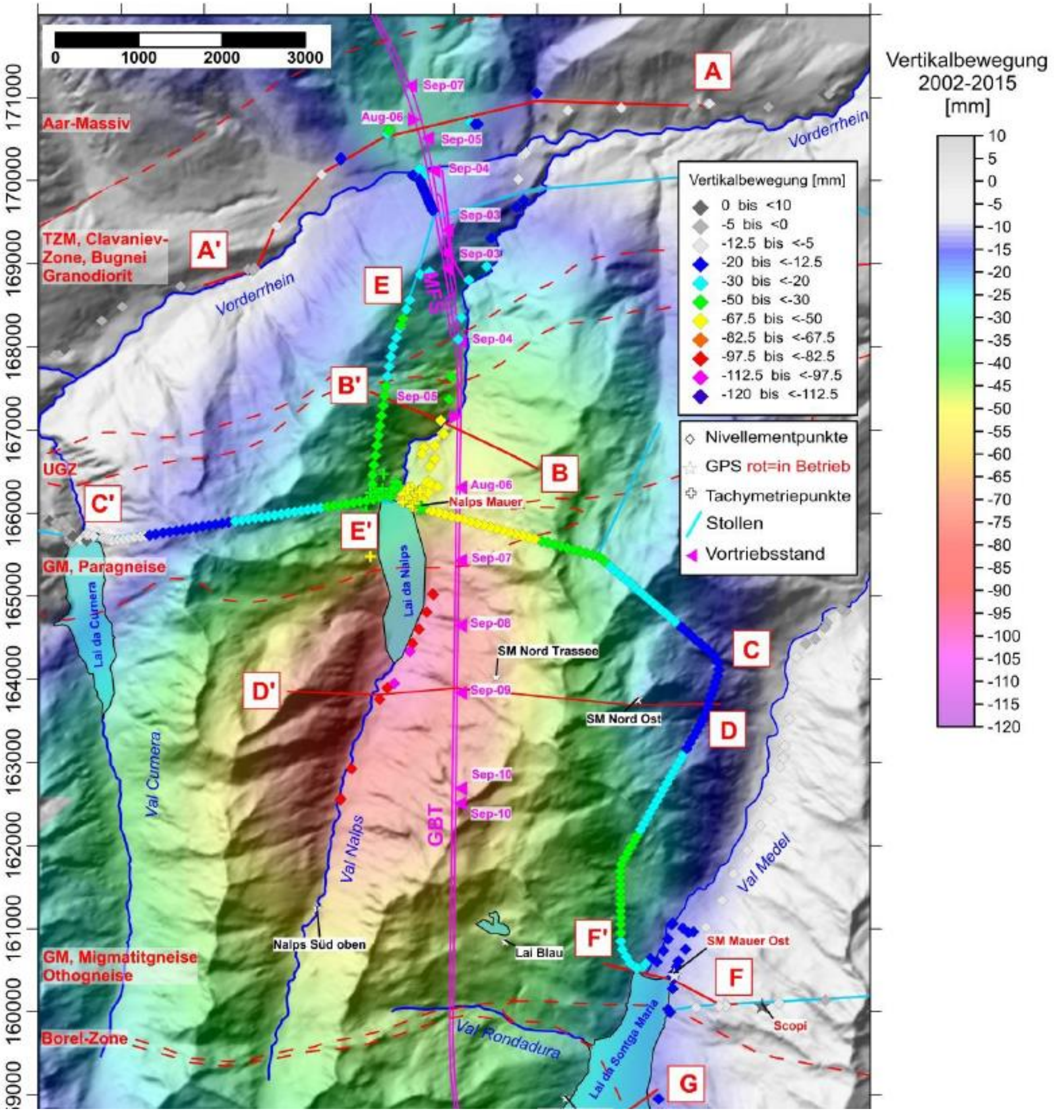




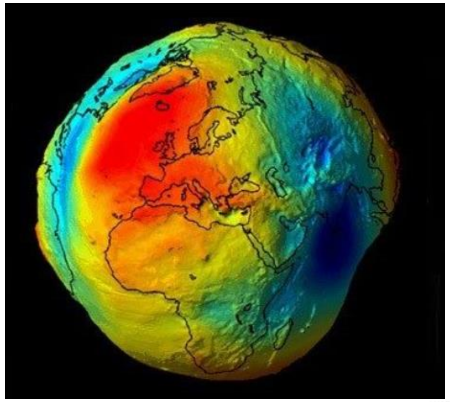
Monitoring above the tunnel

- **Example of the Gottard base tunnel**
  - Tunnel construction works had a drainage effect
  - 10 GNSS permanent stations during 13 years / precise levelling: 100 km every year
  - Vertical movements of up to 12 cm in 13 years in an area of 10 x 15 km

- **In the FCC area the vertical movements might be much smaller, but the FCC is much more sensitive than the Gotthard Base Tunnel.**
  - The FCC area must be monitored
  - The monitoring should start a few years before the construction works



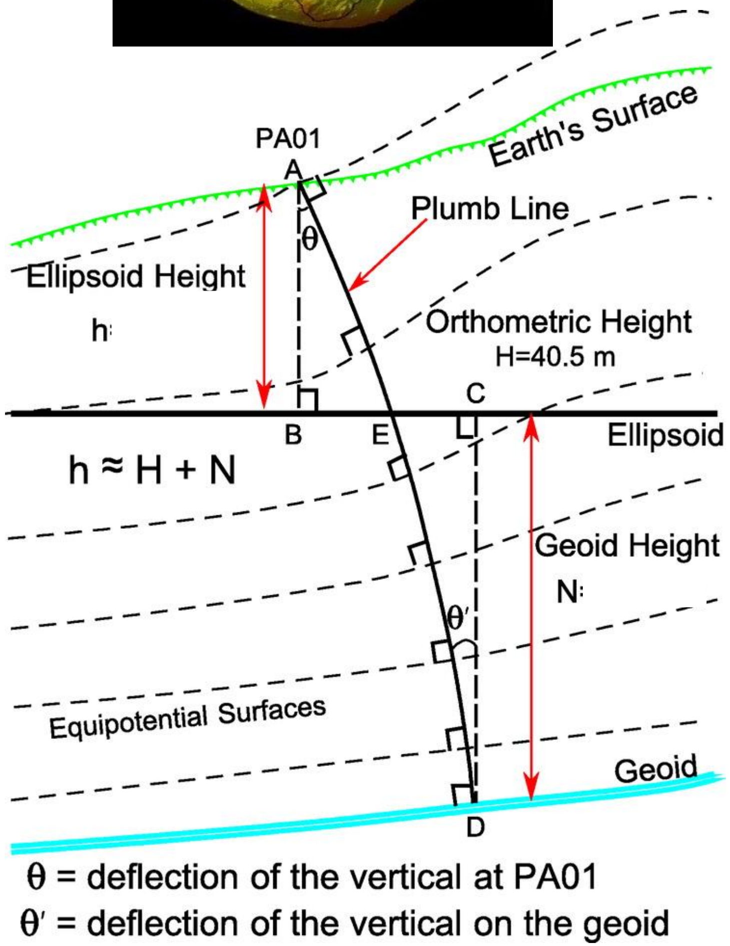
Geoid



- **The geoid is the equipotential surface of the Earth's gravity field which best fits global mean sea level extended under the continents**

- **Gravity equipotential surfaces are not parallel inside the Earth: We need to compute a "pseudo-geoid" computed at the level of the machines**

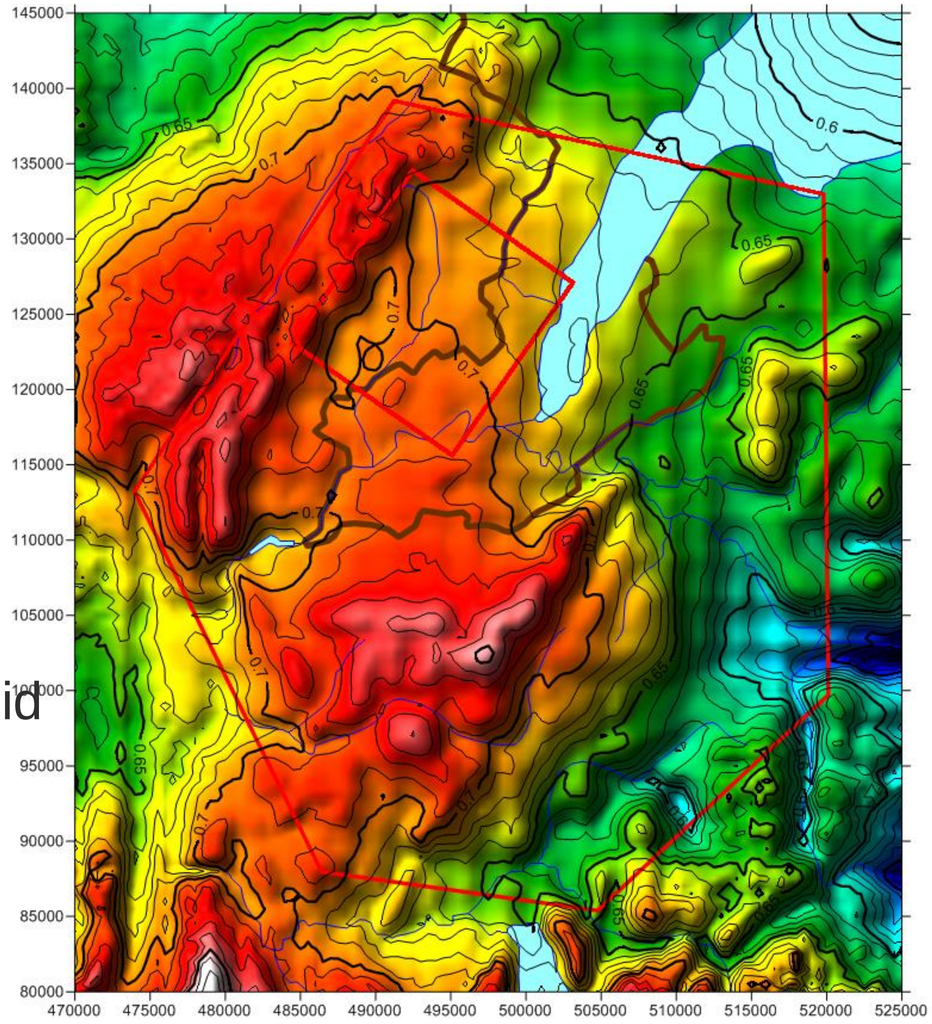
- **The deflection of the vertical (the slope of the geoid) need to be accurately known to align the machine in a Euclidean plane.**



Geoid

Existing models

- Switzerland
  - CHGeo98
  - CHGeo2004
- France
  - QGF98
  - RAF98
  - QGF2016
  - RAF20
- Global Models
  - EGM2008 (A,G,S)
  - GOCO05s (S only)
- CERN
  - CG1985
  - CG2000
- D-A-CH
  - D-A-CH-Geoid
  - European Alps Geoid
- Europe
  - EGG2015

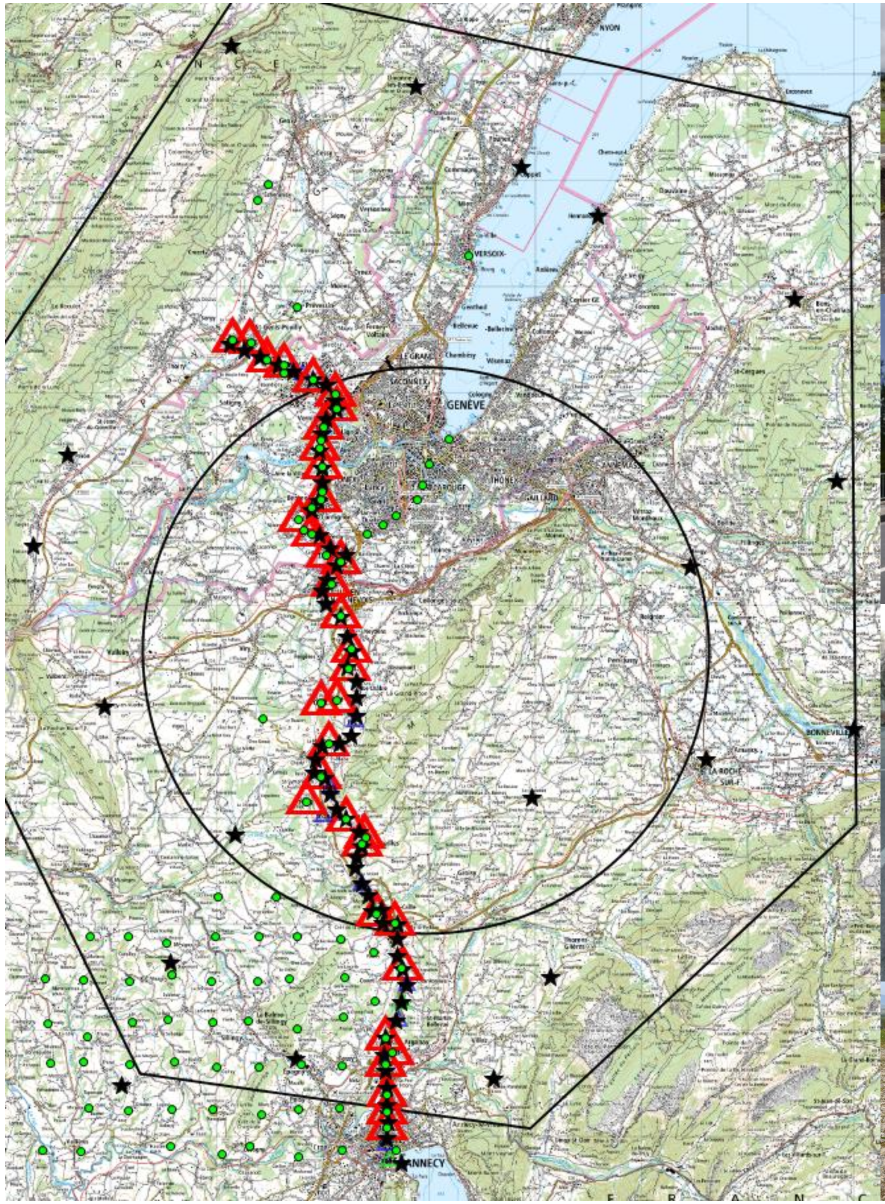


Difference = CHGeo2004 – QGF98

mean offset: 67 cm, standard deviation: 4.1 cm

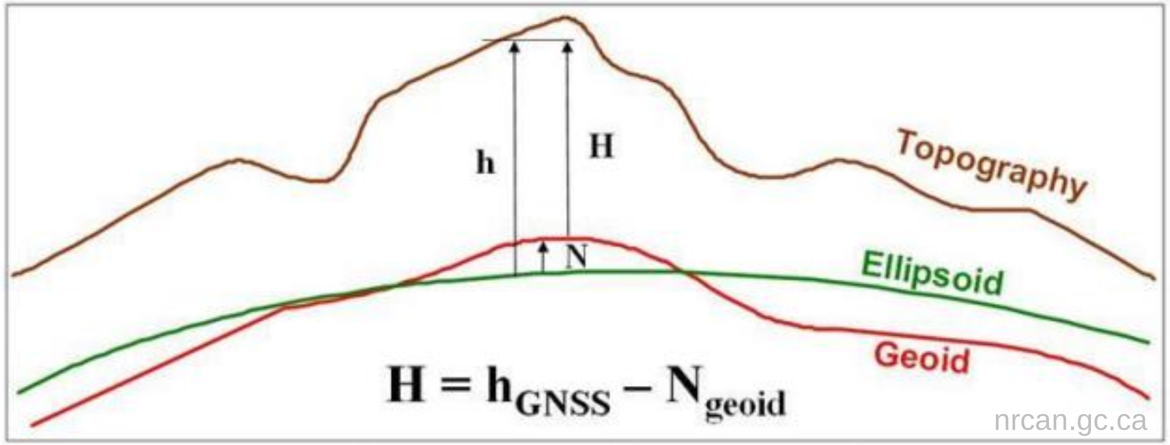
Geoid: control profile

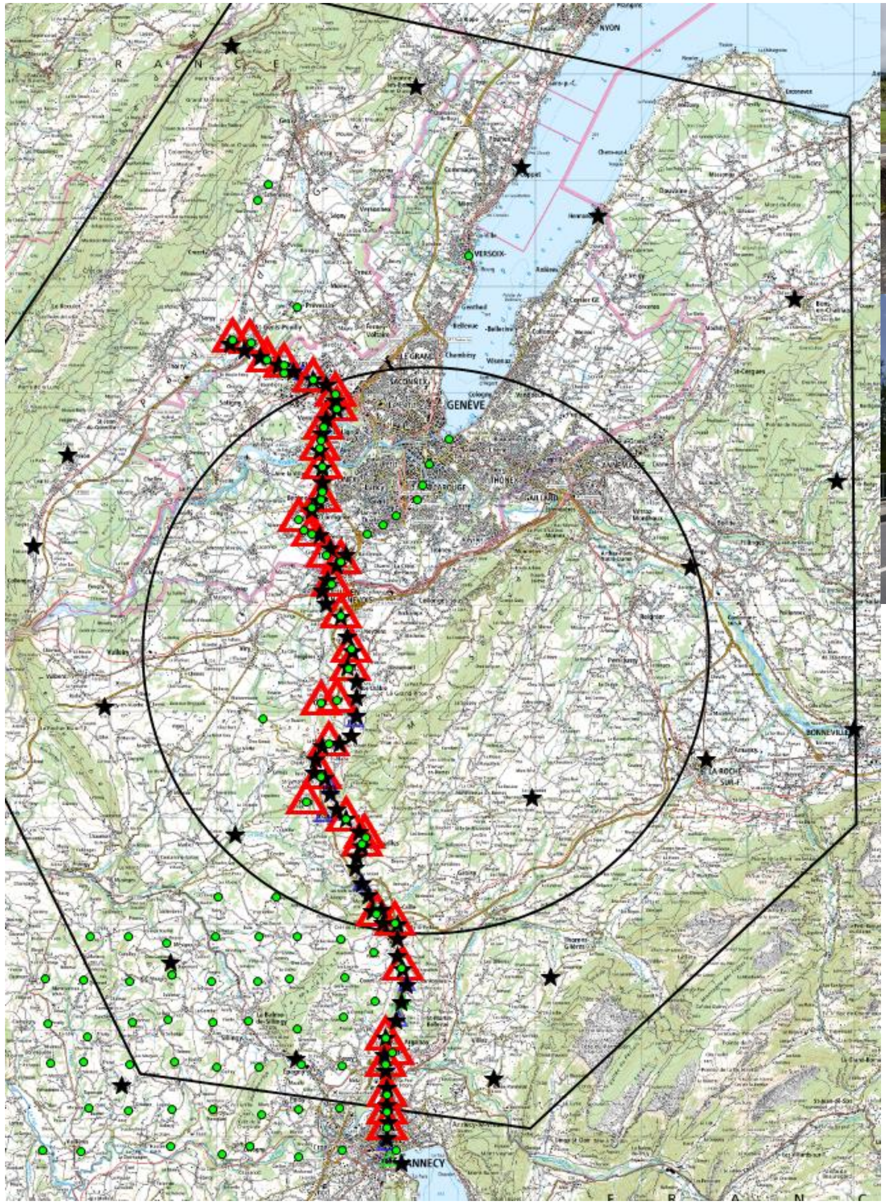
- **Establishment of a test profile**
  - Length 40km
  - Along Swiss and French levelling lines
  - New connection of Swiss and French levelling lines
- **~40 GNSS/levelling stations (△)**
- **~80 Deflections of the Vertical (★)**
- **~50 gravity stations (●)**
- **~50 gravity stations NW of Annecy (filling data gaps)**
- **Purpose:**
  - Independent measurements
  - Validation of the geoid computations and simulations
  - Validation of new instruments



Geoid: control profile

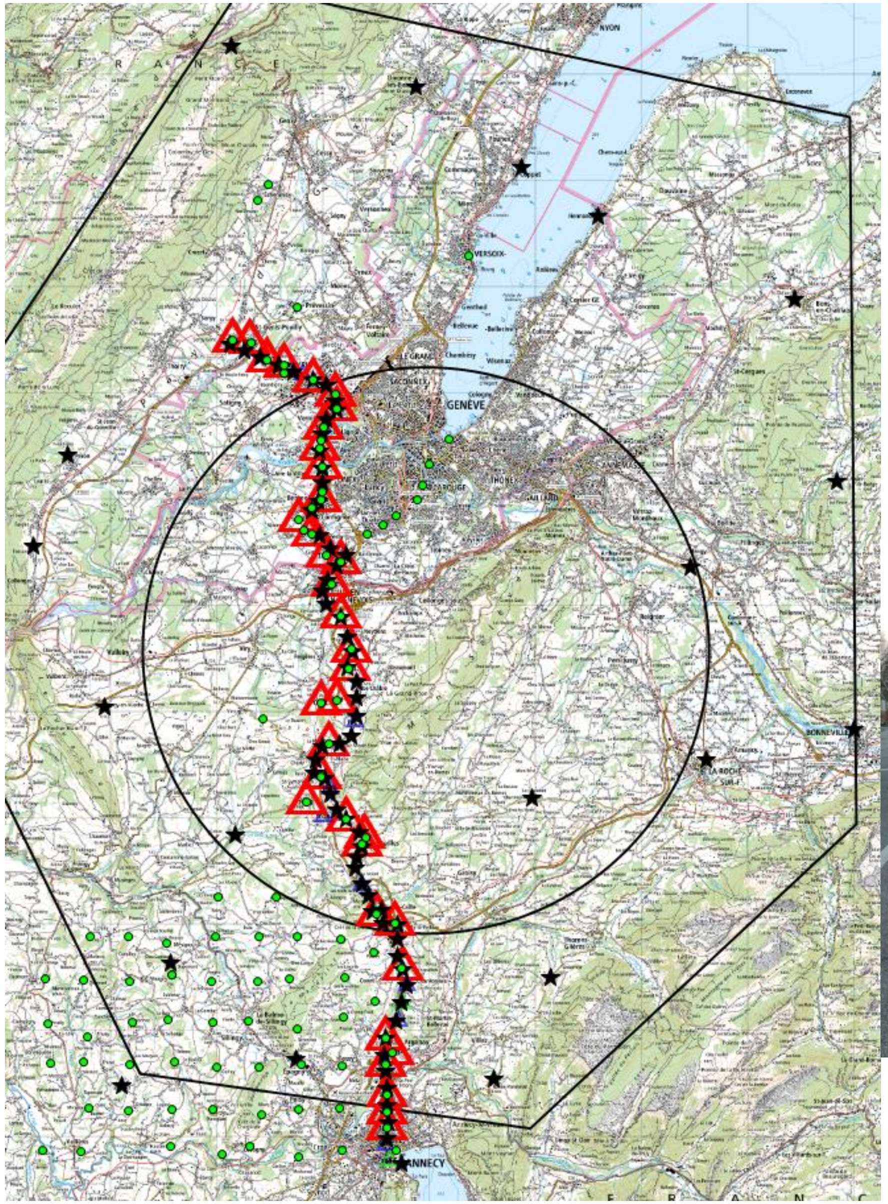
- ~40 GNSS/levelling stations (△)

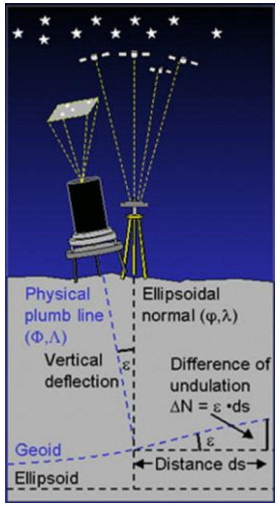




Geoid: control profile

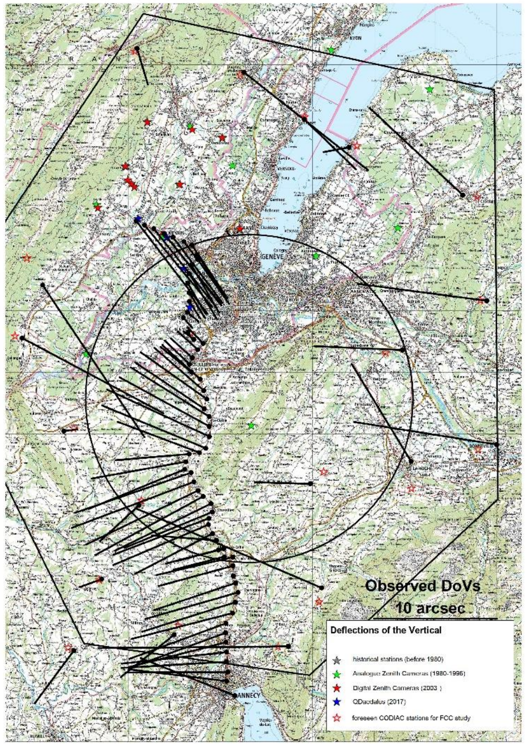
- ~80 Deflections of the Vertical (★)



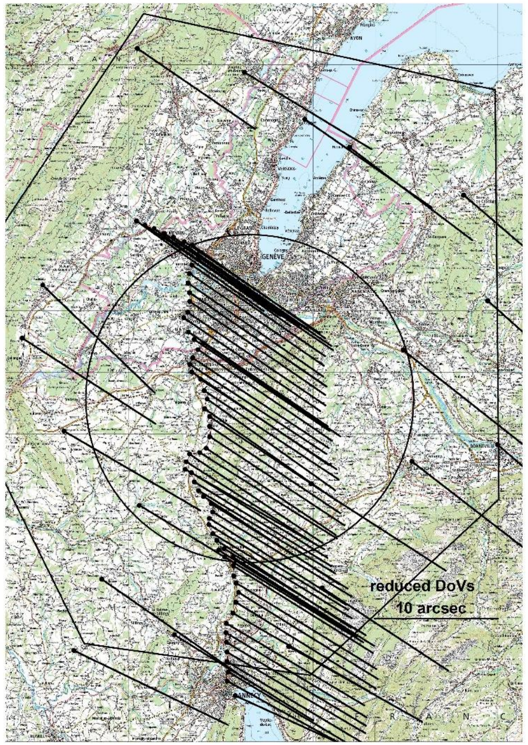


Geoid

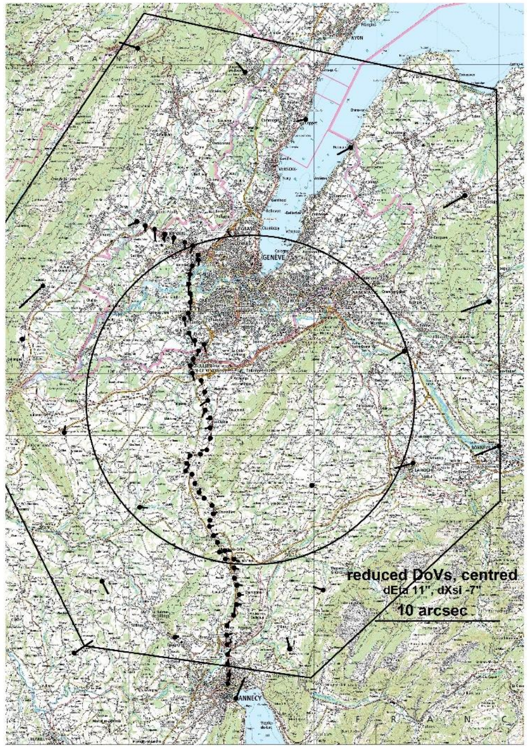
- **Deflection of the vertical along the profile (preliminary)**



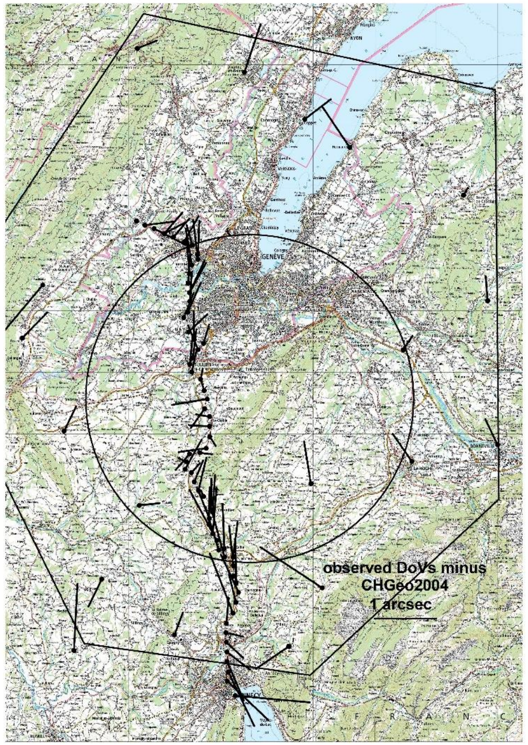
Observed DoV



Reduced DoV



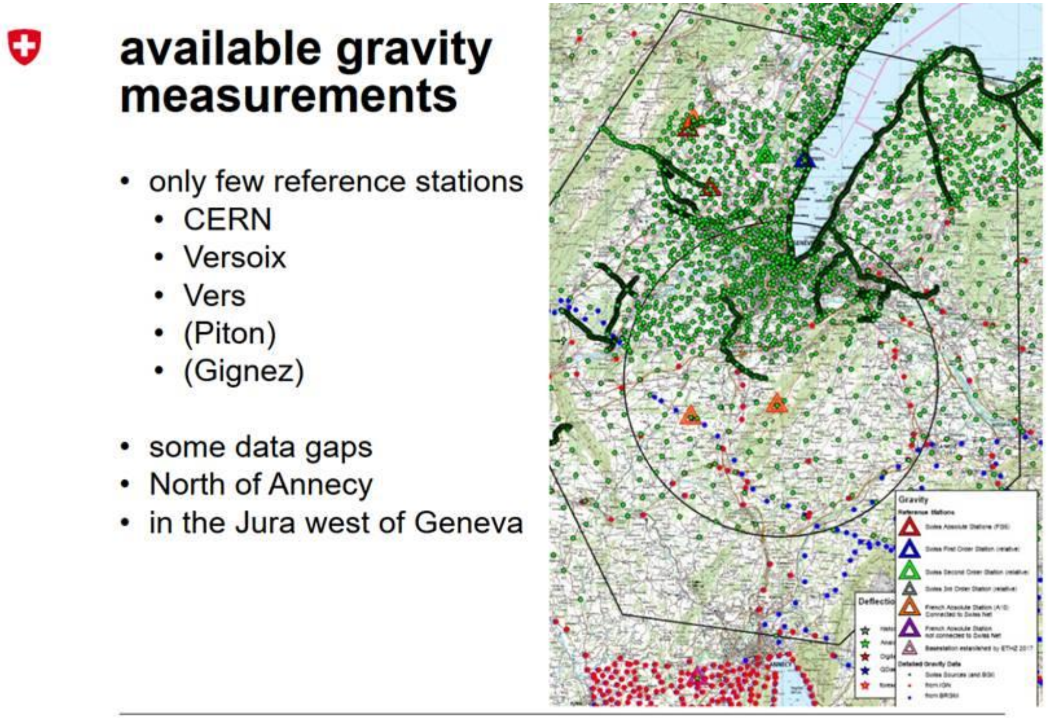
+ mean removed ~ 11" and -7"

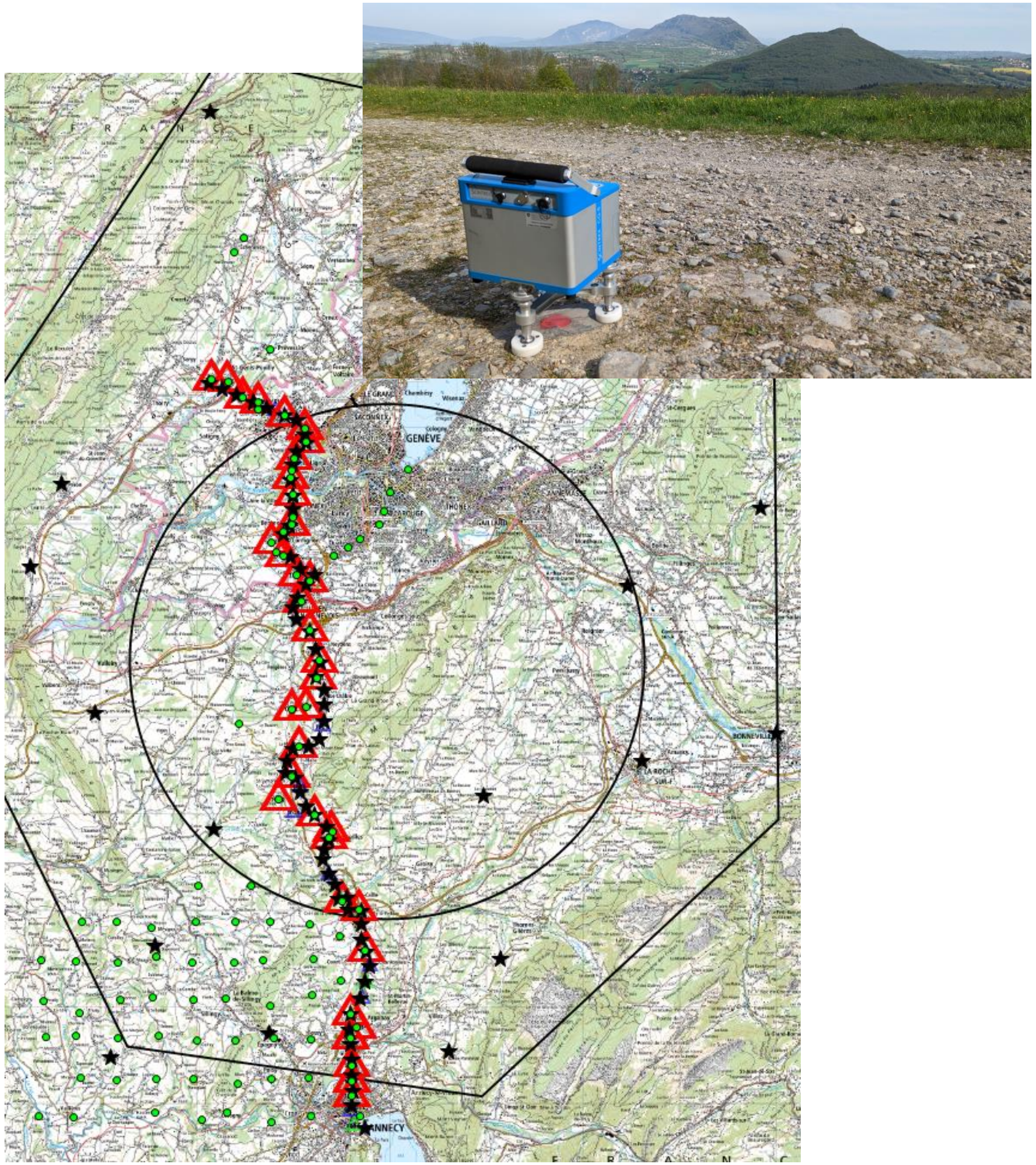


Compared to CHGeo2004 <1"

Geoid: control profile

- ~50 gravity stations (●)
- ~50 gravity stations NW of Annecy (filling data gaps)





Geoid

- **Gravity potential field model is needed to**
  - Establish a consistent height system for FCC
  - Convert geometric heights to physical heights
- **Different types of measuring instruments available and still a field of research**
- **High-Accuracy Profile in FCC area is established for**
  - Validation of geoid computations and simulations
  - Validation of new instruments
  - Validation of new geoid computation methods/software
- **Utimately no levelling needed**
- **Not perfect: different method of computation, give different results**

Link with national geodetic systems

Different reference systems

- **France:**
  - RGF93v2b (ETRF2000@2019.0)
  - NTF (Nouvelle Triangulation Française)

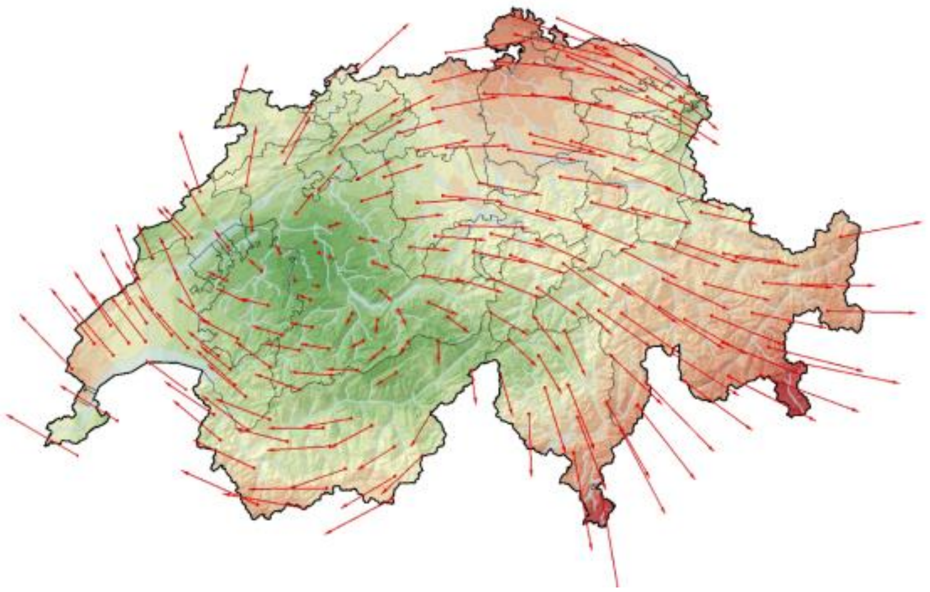
- **Swiss:**
  - CHTRF95 (ETRF93@1993.0)
  - CH1903+
  - CH1903

- **We need transformation models to transform coordinates from one system to another**

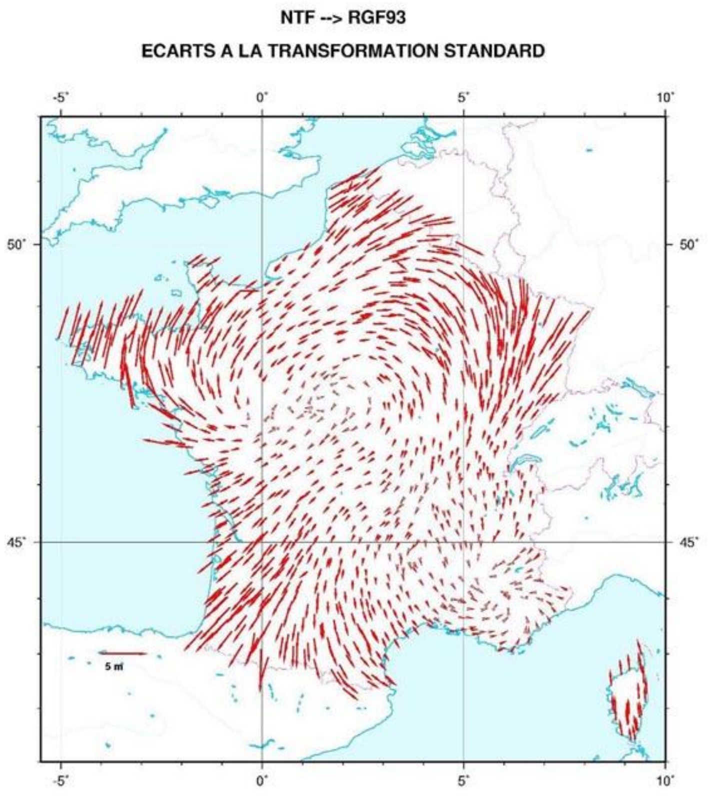
Link with national geodetic systems

Transformation models: Computed from common points

- Transformation grids



swisstopo.admin.ch

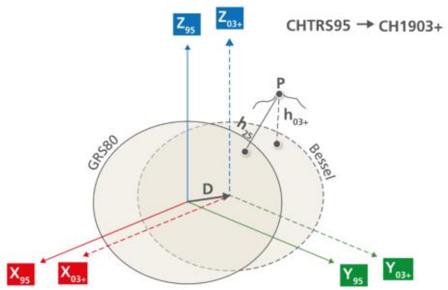


geodesie.ign.fr

Link with national geodetic systems

Transformation models

- **Transformation grids**
- **Geocentric Translation/Rotation**
  - Applying transformation models



Coordinate transformation CHTRS95 -> CH1903+ (X, Y, Z) LV95
= (X, Y, Z) CHTRFyy + (-674.374m, -15.056m, -405.346m)

Transformation parameters from ITRF2020 to past ITRFs.

SOLUTION	Tx	Ty	Tz	D	Rx	Ry	Rz	EPOCH
UNITS---------->	mm	mm	mm	ppb	.001"	.001"	.001"	
	.	.	.	.	.	.	.	
RATES	Tx	Ty	Tz	D	Rx	Ry	Rz	
UNITS---------->	mm/y	mm/y	mm/y	ppb/y	.001"/y	.001"/y	.001"/y	
ITRF2014	-1.4	-0.9	1.4	-0.42	0.00	0.00	0.00	2015.0
rates	0.0	-0.1	0.2	0.00	0.00	0.00	0.00	
ITRF2008	0.2	1.0	3.3	-0.29	0.00	0.00	0.00	2015.0
rates	0.0	-0.1	0.1	0.03	0.00	0.00	0.00	
ITRF2005	2.7	0.1	-1.4	0.65	0.00	0.00	0.00	2015.0
rates	0.3	-0.1	0.1	0.03	0.00	0.00	0.00	
ITRF2000	-0.2	0.8	-34.2	2.25	0.00	0.00	0.00	2015.0
rates	0.1	0.0	-1.7	0.11	0.00	0.00	0.00	
ITRF97	6.5	-3.9	-77.9	3.98	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF96	6.5	-3.9	-77.9	3.98	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF94	6.5	-3.9	-77.9	3.98	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF93	-65.8	1.9	-71.3	4.47	-3.36	-4.33	0.75	2015.0
rates	-2.8	-0.2	-2.3	0.12	-0.11	-0.19	0.07	
ITRF92	14.5	-1.9	-85.9	3.27	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF91	26.5	12.1	-91.9	4.67	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF90	24.5	8.1	-107.9	4.97	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF89	29.5	32.1	-145.9	8.37	0.00	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	
ITRF88	24.5	-3.9	-169.9	11.47	0.10	0.00	0.36	2015.0
rates	0.1	-0.6	-3.1	0.12	0.00	0.00	0.02	

$$\begin{cases} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_B = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_A + T + D \begin{pmatrix} x \\ y \\ z \end{pmatrix}_A + R \begin{pmatrix} x \\ y \\ z \end{pmatrix}_A \\ \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_B = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_A + \dot{T} + \dot{D} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_A + \dot{R} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_A \end{cases} \qquad (1)$$

$$X^E_{yy}(t) = X^I_{yy}(t) + T_{yy} + \begin{pmatrix} 0 & -\dot{R}3_{yy} & \dot{R}2_{yy} \\ \dot{R}3_{yy} & 0 & -\dot{R}1_{yy} \\ -\dot{R}2_{yy} & \dot{R}1_{yy} & 0 \end{pmatrix} \times X^I_{yy}(t).(t - 1989.0) \qquad (2)$$

$$\dot{X}^E_{yy} = \dot{X}^I_{yy} + \begin{pmatrix} 0 & -\dot{R}3_{yy} & \dot{R}2_{yy} \\ \dot{R}3_{yy} & 0 & -\dot{R}1_{yy} \\ -\dot{R}2_{yy} & \dot{R}1_{yy} & 0 \end{pmatrix} \times X^I_{yy} \qquad (3)$$

Link with national geodetic infrastructure

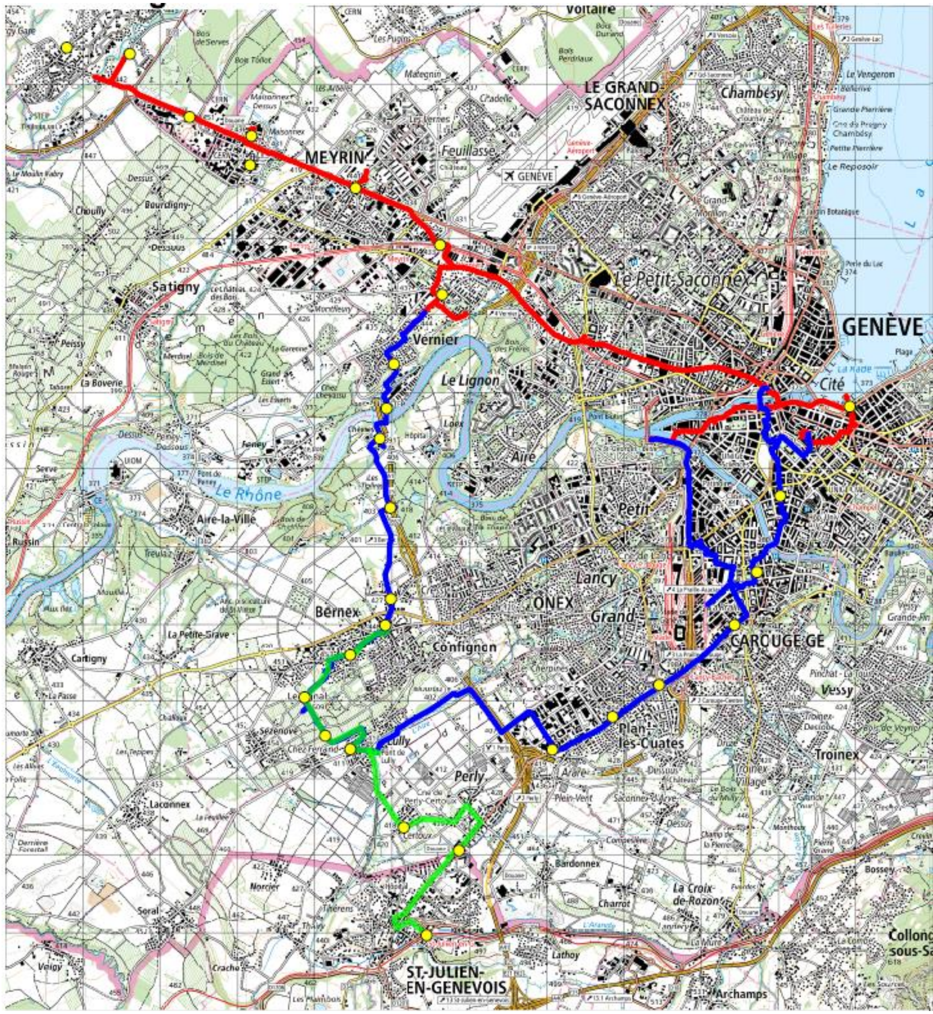
Height

- Green line by CERN May 2021
- Blue Lines by Canton Geneva 2011/2012
- Red Lines by swisstopo 1998

- Yellow Points Gravity measurements April 2022

- Closed levelling circuit in the vicinity of Geneva
  - Without corrections: 0.9 mm
  - With corrections[1]: 0.6 mm
- Closed levelling circuit in the historical center of Geneva
  - Without corrections: 0.5 mm
  - With corrections[1]: 0.5 mm

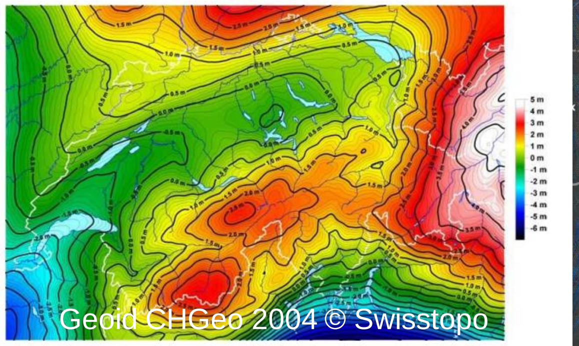
- Height differences CH – F official heights
  - St. Genis 32.1 cm
  - St. Julien 31.0 cm
- Height differences CH – F corrected heights[1]
  - St. Genis 36.1 cm
  - St. Julien 34.8 cm



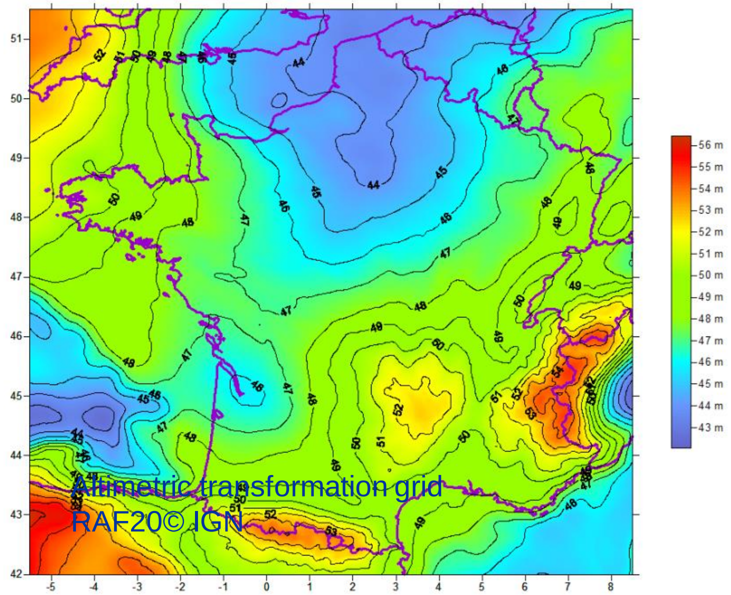
[1] Heights transformed to Normal Heights (gravity corrected)

Software: CSGeo

- **CSGeo is the in-house CERN geodetic transformation software developped by the BE-GM-APC section**
- **Update of coordinate system definitions and transformation models**
- **Complete management of the French and Swiss altimetric system (~30 cm of difference observed in the CERN area)**
- **A Dynamic Link Library (DLL) is provided to call transformation functions from external program**
  - Avoid to use external applications like Reframe or Circe


Geoid CHGeo 2004 © Swisstopo

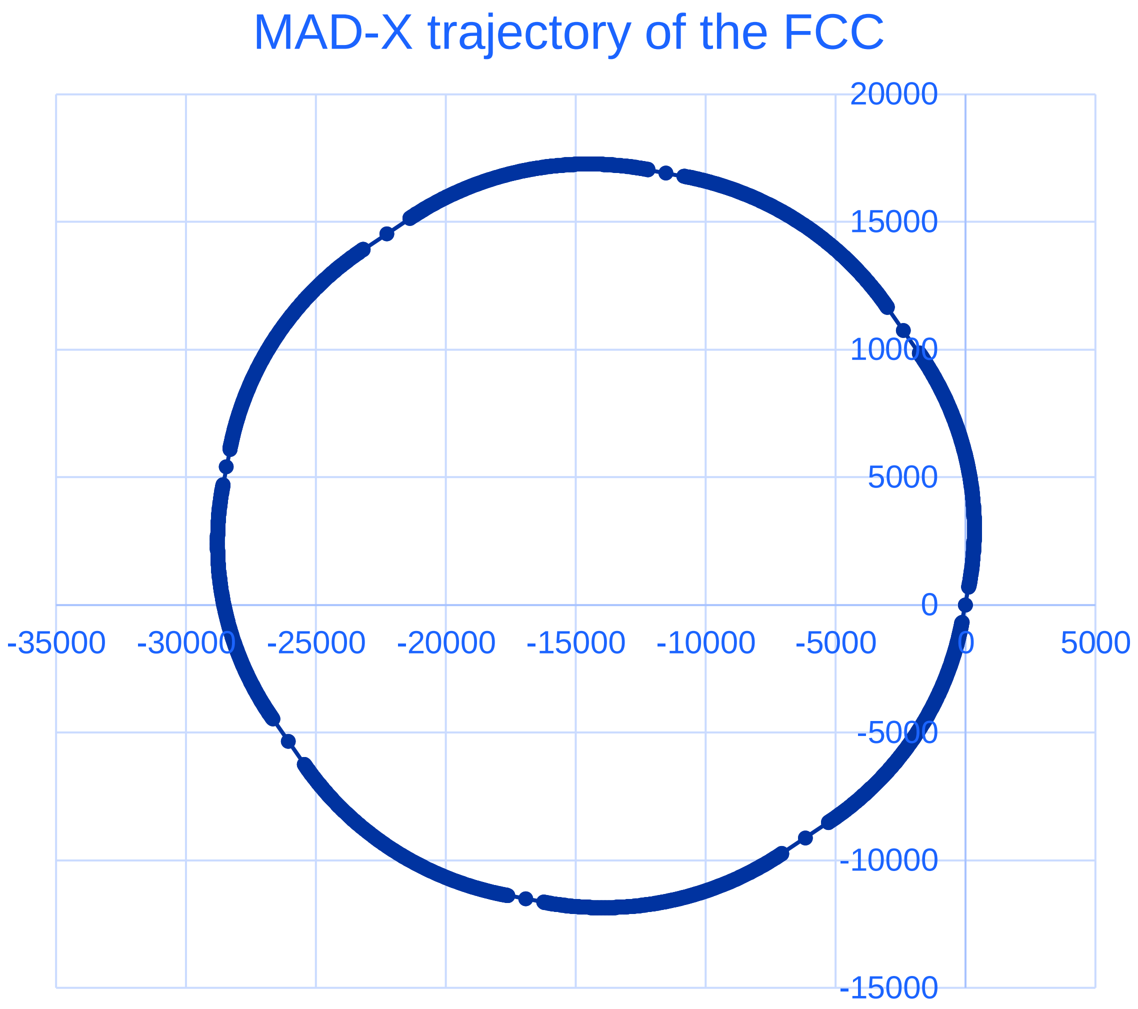
http://geolabpasaia.org/gnss/agi/maps/EU-DenseVelocities.html


Altimetric transformation grid RAF20© IGN

From MAD-X to real world

MAD-X

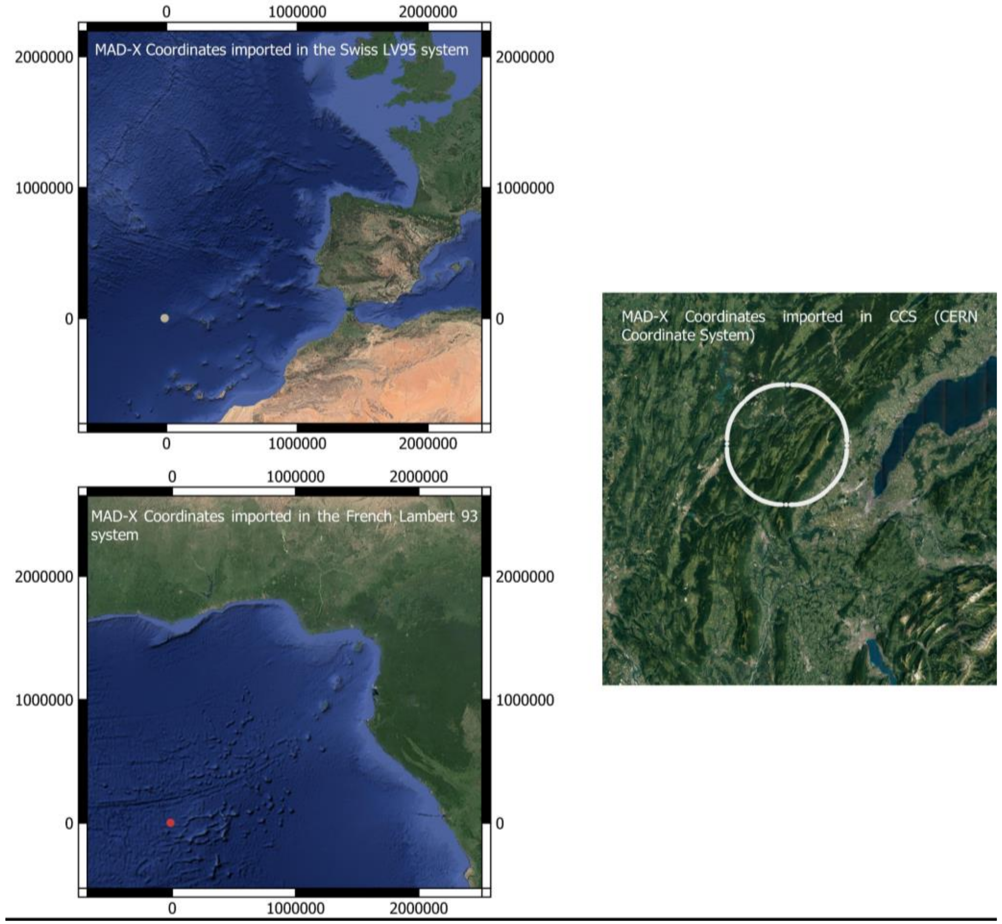
- **Generate the optimal beam trajectory of the FCC**
- **Generate a 3D positioning of all the beam components**
- **Coordinates of the beam components are expressed in an arbitrary system**



From MAD-X to real world

MAD-X

- These coordinates are not sufficient to position the FCC in the real world
- There is no chance to build the FCC tunnel where it is expected using raw MAD-X coordinates
- Each projection distorts the reality and may introduce scale factor. Shifting and rotating the coordinates by a chosen value is not a valid option



From MAD-X to real world

Topocentric to geographic coordinates

- The MAD-X coordinates can be converted into geocentric coordinates, knowing the position of one initial point and initial azimuth
- The plane in which the trajectory is computed is considered tangent to the ellipsoid
- Latitude, longitude and ellipsoidal heights of all points can then be computed
- If the tunnel is bored following a defined slope to stay into specific geological layers, coordinates can be transformed into the tangential plane

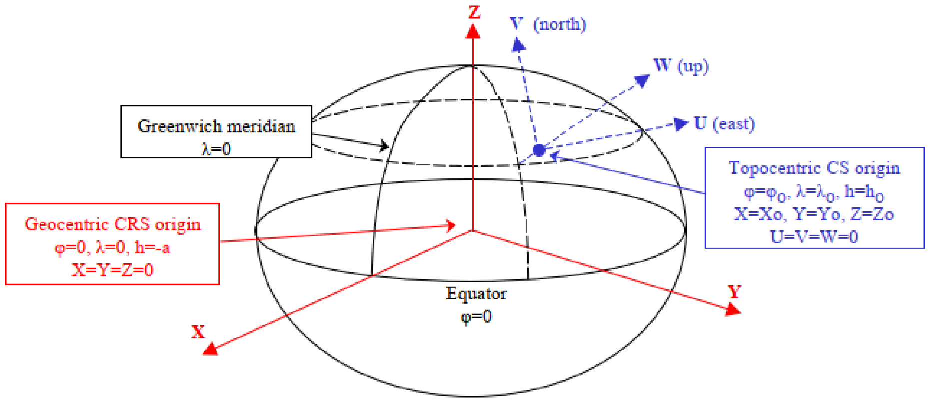


Figure 12 – Topocentric and geocentric systems

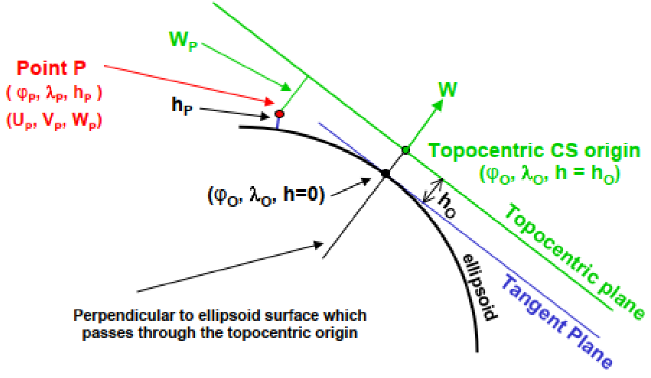


Figure 13 – Topocentric and ellipsoidal heights

From IOGP Publication 373-7-2 – Geomatics Guidance Note number 7, part 2 – September 2019

Conclusion

- **Increasing the size of the accelerators requires higher accuracy**
- **Reference network and the geoid model must be adapted and upgraded**
- **New terrestrial and satellites techniques and instruments allow to reach higher accuracy even for larger projects**
- **Ongoing developments and research works for the FCC feasibility study**

Thank you for your attention

References

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